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MAGNETIC BUBBLE RESEARCH

Millard G. Mier, PhD
Electronic Research Branch
Electronic Technology Division

November 1979

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Project Engineer

FOR THE COMMANDER

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Geometrical analysis techniques are used to derive computer memory system characteristics to support a hypothetical but realistic Air Force tactical mission scenario. Commercially available computer memory systems which might fulfill this requirement are reviewed and found unsuitable. Four emerging technologies which appear to have potential for fulfilling this requirement in the mid-1980's are reviewed and projected characteristics of a suitable capacity system based on each technology derived. The most promising technology, over

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20. ABSTRACT (Cont'd)

magnetic bubble memory, is examined and a major barrier to development is found to be the accurate characterization of materials supporting micron-sized magnetic bubbles.

Standard techniques are examined for characterization of materials supporting very small magnetic bubbles. The failing of all techniques is optical microscopic resolution of these bubbles. Three new techniques for this characterization, based on magnetic susceptibility changes with applied magnetic field, are examined and found to be suitable for small magnetic bubbles. A fast running Control Data Corporation (CDC) FORTRAN EXTENDED computer analysis program is described for analyzing experimental data and calculating all the static bubble materials parameters.

AFAL-TR-79-1128

FOREWORD

This report was prepared by the Electronic Research Branch, Electronic Technology division, Air Force Avionics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson AFB, Ohio under U.S. Air Force Office of Aerospace Research Project 2305, Task 2305R2, Work Unit 2305R264 "Magnetic Bubble Research". Dr. Millard G. Mier (AFAL/DHR) was the project engineer for the work described.

This report was submitted by the author June 1979.

Major contributions to the experimental work on microwave measurements of magnetic bubble materials by Dr. Hilmer W. S. Swenson, Donald Locker, Dr. Thomas Stakelon, Pradeep S. Limaye and Prof. Philip E. Wigen are acknowledged. The laser spatial filtering, performed by Robert A. McDonald and Dr. Robert L. Johnson, is appreciated greatly. Full analysis of the af susceptibility measurements was initiated by Prof. Clark W. Searle, and the af and rf experimental measurements are due to Dr. Iman Maartense, Michael Globe, Dr. Joseph Omaggio, and Alan Parker. John Blasingame participated in all aspects of this effort.

The support of Robert D. Larson, who until his retirement in March 1979 was the author's supervisor, is deeply appreciated. Support from Ms. G. Doben and AFAL/TSR in the typing and assembly of this manuscript is gratefully acknowledged.

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INTRODUCTION

The desirable properties of magnetic bubble memories for Air Force remote-vehicle application are well-known. The properties of small physical size, low power, light weight, radiation tolerance, and low cost are combined with nonvolatility and block-access capability which make magnetic bubbles an ideal substitute for discs, drums, and modest-capacity tape recorders. Magnetic bubble memories fit precisely into the computer hierarchy in place of presently-used electromechanical technologies, but with improved operating characteristics.

The major challenge to magnetic bubble memories has been to provide enough bit capacity in a small volume for Air Force remote vehicle applications. The first Air Force Avionics Laboratory program to construct bubble memories uses four to six micrometer diameter bubbles and approximately 10^5-bit chips.[1] To keep the reliability and lifetime high, only a few thousand chips can be wired together. Thus the practical limit to memory capacity using four to six micrometer bubbles is about 3×10^8 bits. The volume required for a bubble memory with this high a capacity becomes rather large (several cubic feet), so the typical disc/drum capacity of about 1.5×10^7 bits, which can be accomplished in about one cubic foot, is a practical goal for the first (large bubble) memory systems. It is typical of emerging technologies that users are not satisfied with easily attainable goals, and magnetic bubbles are no exception. Even before the work to construct large bubble memories was started, the need for lower volume and higher total bit capacity was apparent. In order to attain a capacity of 2×10^9 bits in no more than 0.5 cubic feet, a major advance in magnetic bubble technology was needed. Reliability considerations continue to dictate that no more than a few thousand chips be used, and system volume considerations dictate that the number of coil sets be kept as low as possible. Thus the chip capacity must be the order of 10^6 bits. While four to six micrometer diameter bubbles could be used in a chip of this capacity, the chip would be several square inches.

Maintaining a uniform bias and rotating magnetic field over this area is a complex problem. A simpler approach is to use small (two micrometer diameter) magnetic bubbles. This is the second group of AFAL program aimed at million-bit or larger chips and systems with capabilities up to a few billions of bits.[2] Such memory systems could fill the position in computer hierarchies now held by moving-head discs and also many recorder application. Large improvements in performance, ruggedness, reliability, and lifetime should be achieved by utilizing small bubble technology. Recording and processing sensor data, as from side-looking radar, forward-looking infrared, or visual imagery, can require much larger data memories. Section II presents the analysis of the in/out bit rate and total on-board storage capacity that would be needed for a specific (but hypothetical) border surveillance task. It is shown that 10^{12} bits storage, with an in/out data rate of 50 Mbit/second is needed on-board a remote airplane. This capacity would require over a hundred cubic feet volume if implemented using small bubbles, and it is evident that another major advance in magnetic bubble technology is needed. The approach chosen is to use lattice file, whole water chips which could achieve at least 2×10^8 bits per chip and 780 Kbit/second in/out rates. Multiplexing sixty-four of these chips would give the desired 50Mbit/second data rate. This research is the subject of Contract No. F33615-76-C-1198.

The in-house portion of this basic research has three aims: (1) to perform the system concepts analysis of what the Air Force will need to perform a mission in the mid-1980's time frame, (2) to ensure that contractor efforts actually contribute to achievement of the goals determined during the system concepts analysis, (3) to contribute new ideas to the contractor and, where needed, to help the contractor overcome impasses in his approach. Section III addresses a specific impasse: optical methods are inadequate to characterize magnetic bubble materials when the thickness and bubble diameter are only three or four times the wavelength of visible light. A new non-optical technique for characterizing magnetic bubble materials is described in this section and compared to the more traditional bubble materials characterization techniques. Finally, the computer program used in performing this new analysis is listed in the Appendix with instructions for use.

SECTION II

GEOMETRICAL ANALYSIS OF AN AIR FORCE TACTICAL MISSION SCENARIO

1. INTRODUCTION

Military power sometimes has been equated with numbers of planes, tanks, ships, guns, and men, but there is one critical element in addition - that is information. All weapons are completely useless without specific information on where the targets are located. It is the function of reconnaissance to explore the enemy territory and gain information about the location of possible threats or targets. This information may be obtained in the form of photographs, radar imagery, infrared imagery, or other sensory data. Modern electronics usually reduces this information into digital form to facilitate handling by digital computer. The transmission of this information by various types of communication systems and the manipulation of the information into a form usable for command and control decision making is the function of data processing. Regardless of how the information originated, it ultimately will reside at some state of processing in a computer mass memory. It is the purpose of this analysis to show how the development of smaller, lighter, higher capacity, faster mass memories has a direct and immediate effect on the use of tactical weapons. Just as information is a critical ingredient of military power, so are the memories which contain this information.

2. GEOMETRICAL SCENARIO ANALYSIS

Military applications for solid-state mass memories include such areas as: radar video recording, electronic intelligence, reconnaissance, surveillance, and general tape recorder replacement. For purposes of illustration consider one of the critical tactical problems discussed by Dr. Malcomb Currie, director of DDR&E, in his statement before congress on the Fiscal 1977 budget[3] (Figure 1). That problem is how to counter a "blitzkrieg" of massed, highly mobile, heavy armor such as we may some day face in Europe. The solution to this problem was suggested by Dr. Currie through the use of improved command/control "force level multipliers" together with integrated battlefield surveillance, target acquisition,

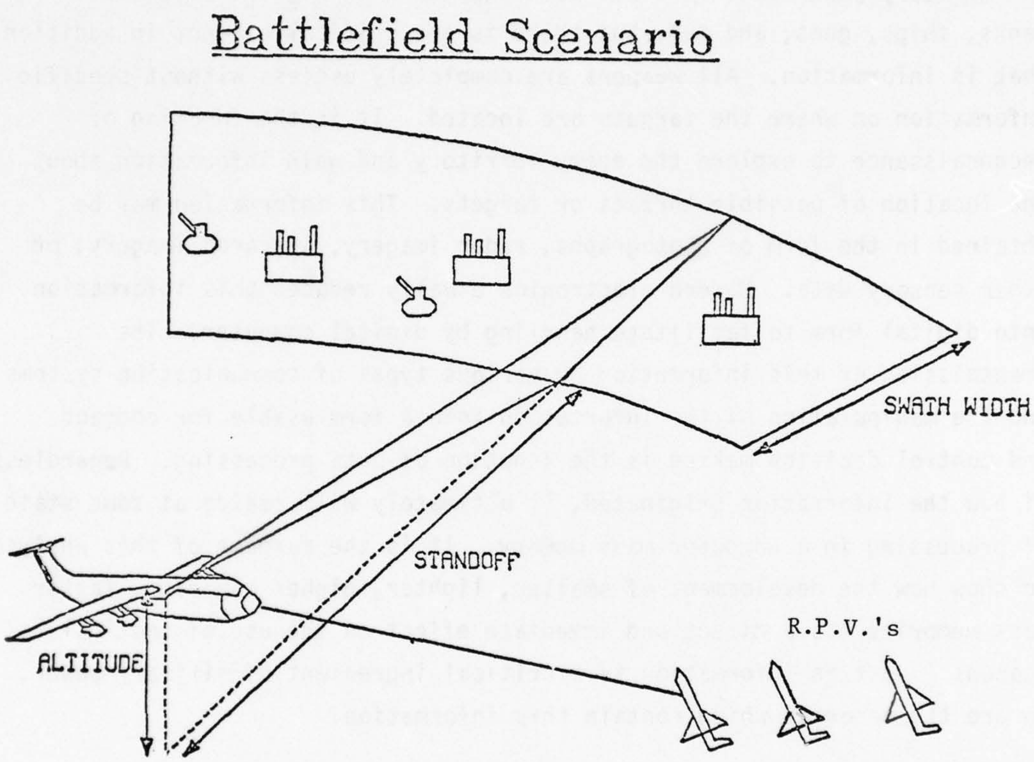

Figure 1. Hypothetical Battlefield Scenario

high altitude sensors, stand-off synthetic aperture radars, secure communications, computers capable of real time processing of sensor data, and large numbers of surgically accurate weapons with less sophistication and low cost.

Small solid-state mass memories are one of the key components along with high-speed computers and low-cost strike Remotely Piloted Vehicle (RPV's) to the implementation of this strategy. In order to store data on an area representing the size of West Germany (2.6×10^{12} sq. ft.), for example, with a resolution of 1 yard and 1 bit of gray scale would require 0.29×10^{12} bits of memory. All present-day, on-line memories with this capacity require critical mechanical alignments (and are thus fragile). They typically occupy at least a thousand cubic feet of air-conditioned, vibration-free computer room space. Within these constraints, it is a remarkable achievement that three versions have found use. If one assumes a hypothetical number of 10,000 targets in this area, free to move at up to 50 mph, and that we wish to know their position accurately to within 100 feet, we must update the data on all targets every 1.36 seconds and the memory must be capable of an access time no greater than 1.36×10^{-4} seconds. To fit aboard a modern fighter aircraft would require that the memory be no more than a couple of cubic feet in size and weigh less than a few hundred pounds.

3. CURRENTLY AVAILABLE TECHNOLOGIES

A typical capacity for present-day large data base mass memories is about 10^{12} bits. A large reel of magnetic video tape will hold about 10^{11} bits and some means of mechanically changing reels must be provided to reach 10^{12} bits. All present-day, on-line memories with this capacity require critical mechanical alignments (and are thus fragile). They typically occupy at least a thousand cubic feet of air-conditioned, vibration-free computer room space. Within these constraints, it is a remarkable achievement that three versions have found use. The characteristics of currently available 10^{12} bit mass memories are summarized in Table 1.

TABLE 1

CURRENTLY AVAILABLE 10^{12} BIT MASS MEMORIES

	Precision Instruments	Ampex Terabit	IBM 3850
System Capacity	1×10^{12} bits	1.5×10^{12} bits	2×10^{12} bits
Data Density	3×10^{6} bits/sq. cm.	1×10^{5} bits/sq. cm.	5×10^{4} bits/sq. cm.
Recording Area	4×10^{5} sq. cm.	4×10^{7} sq. cm.	4×10^{7} sq. cm.
Access Time	5 seconds	20 seconds	5 to 8 seconds

All of these systems use some kind of plastic tape with information stored magnetically or optically (as laser burned holes) with mechanical access. The slow access times, together with the very large physical size, preclude their use in any practical airborne or spaceborne system foreseen today.

4. EMERGING TECHNOLOGIES

Prospects for improving mass memories in the future look extremely promising. The four leading candidates for 10^{12} bit solid state memories in the next ten years are: semiconductor Charged-Coupled Devices (CCD's), magnetic bubbles, optical, and electron beam accessed memories. Semiconductor CCD's were selected to illustrate the state of the art in semiconductor memories. The Mnemonics 65K CCD chip is the largest capacity semiconductor memory chip currently on the market. Data on this chip together with projections for CCD technology presented by Dr. W. Kosonocky at the Stanford Research Institute Symposium on Advanced Memory Concepts[4] are listed in Table 2. The main disadvantage of today's CCD technology is the very large standby power necessary to constantly recirculate and refresh data, since this is a volatile type of memory. Substantial progress can be anticipated over the next ten years if one assumes that one micron design rules are common practice, that five inch whole wafer technology is available with yields of at least 20%, and that some combination of CCD techniques with non-volatile Metal Nitride Oxide Semiconductor (MNOS) technology will become available to produce a nonvolatile high-capacity CCD which would not require standby power. If these three assumptions can be realized without increasing the cell size too much, then CCD's may become much more competitive in the future.

TABLE 2

SEMICONDUCTOR MEMORIES

	Current Capabilities	Projected Capabilities in 1985
Type	CCD (NMOS - Double Polysilicon)	CCD
Volatile/Non-Volatile	Volatile	Volatile
Category	Read/Write	Read/Write
Cell Size	22.7 x 22.7 Microns	4 x 4 Microns
Chip Size	218 x 235 mils	5 in Diam Wafer
Access Time	0.4 to 2 mSec	0.1 to 20 mSec
I/O Data Rate	5 Mbps	10 Mbps
Volume	2404 cu ft for 10^{12} Bits	14 cu. ft for 10^{12}
Weight	269,248 lbs for 10^{12} Bits	1570 lbs for 10^{12}
Power	246,154 Watts Standby for 10^{12}	1 - 10 KW Standby for 10^{12}
Temperature Range	0° to 70° C	0° - 70° C
Cost	10 m¢/Bit	.1 to 10 m¢/Bit

Present and projected characteristics for optical memories are based primarily on the Precision Instruments Unicon 190 system as described by Kaczorowski[5] and Dell[6] (Table 3). This system utilizes a laser to burn small holes in a metal film on a polyester strip. A 10^{12} bit capacity system is presently available at relatively low cost. However, this system requires relatively high power for the read laser and exhibits very slow access speeds due to mechanical motion necessary for changing the storage strip. Experimental systems have been built without mechanical motion, but the costs of the optics become prohibitive: a separate read station must be provided for each storage strip. It is anticipated that the density of storage in these systems will increase by about a factor of ten on the medium as one micrometer cell sizes are achieved, and that this will lead to somewhat faster access and lower system volume. Optical memory systems, however, will always be limited by the laser in power efficiency as well as in size and weight. In addition they require precision, critical alignments which are difficult to maintain in aerospace environments.

TABLE 3

OPTICAL MEMORIES

	Current Capabilities	Projected Capabilities in 1985
Type	Bit by Bit	Bit by Bit
Volatile/Nonvolatile	Non-Volatile	Non-Volatile
Category	Archival	Archival
Cell Size	3.6 x 3.6 uM	1 x 1 uM
Chip Size	4.75 x 31.25 in	4 x 4 in
Chip Capacity	2.8 x 10^9 Bits	10^{10} Bits
Access Time	10 Sec	1 Sec
I/O Data Rate	4 Mbps	10 Mbps
Volume	850 cu ft for 10^{12} Bits	27 cu ft for 10^{12} Bits
Weight	350 lbs for 10^{12} Bits	300 lbs for 10^{12} Bits
Power	2500 Watts for 10^{12} Bits	2500 Watts for 10^{12} Bits
Cost	0.1 m¢/Bit	0.06 m¢/Bit

Electron beam accessed memory capabilities are displayed in Table 4, where present capabilities are those listed by General Electric Co. and Microbit Corp. and 1985 projected capabilities are based on the work of G.E. under contract F33615-76-C-1322[7]. This technology has the potential of becoming one of the least expensive and fastest of any of the current candidates due to the extremely high potential density of the data on the target and the speed with which an electron beam can be deflected. It does have the usual disadvantages of tube technology in requiring a vacuum envelope and high voltage power supplies and will most likely require precision, critical alignments in the deflection elements. This tends to make it somewhat heavier, more bulky, and more fragile than is desired for an aerospaceborne memory, so that this must be carefully traded against speed and cost.

Table 5 lists the current status and system characteristics of magnetic bubble mass memories based on the Texas Instruments Inc. work under contract F33615-75-C-1228[8] and the projected characteristics of bubble-lattice-file memories based on work at Rockwell International under contract F33615-76-C-1198[9]. The outstanding advantages of magnetic bubble technology are extremely small size, weight, and power with relatively low cost. The present disadvantages are a somewhat limited

TABLE 4

ELECTRON BEAM MEMORY

	Current Capabilities	Projected Capabilities in 1985
Type	MOS Target (Read/Write)	Ion Implanted Si Target (Archival)
Cell Size	4 x 4 Microns	0.1 uM x 0.1 uM
Chip Size	1 in Wafer for 32 Mbits	3 in Diam Wafer for 10^{11} Bits
Access Time	10 – 30 uSec	30 uSec
I/O Data Rate	10 Mbps	10 Mbps (Single Channel)
Volume	1.67 cu ft for 32 Mbits	3.6 cu ft for 10^{12} Bits
Weight	70.4 lbs for 32 Mbits	700 lbs for 10^{12} Bits
Power	256 Watts for 32 Mbits	256 Watts for 10^{12} Bits
Temperature Range	-55° C to +125° C	-55° C to +125° C
Total System Cost	50 m¢/Bit	0.02 m¢/Bit

TABLE 5

MAGNETIC BUBBLE MEMORIES

	Current Capabilities	Projected Capabilities in 1985
Type	Permalloy Bar File	Bubble Lattice File
Cell Size	5 uM Bubbles, 22 uM x 22 uM	2 uM Bubbles, 3 uM x 3 uM
Access Time	1.5 mSec	80 uSec
I/O Data Rate	2 Mbps	50 Mbps
System Volume	2.6 cu ft for 100 MBits	1.4 cu ft for 10^{12} Bits
System Weight	156 lbs	157 lbs for 10^{12} Bits
System Power	51 Watts	102 Watts for 10^{12} Bits
Temperature Range	-25° C to +125° C	-55° C to +125° C
Cost	50 m¢/Bit	0.25 m¢/Bit

temperature range (which is still much wider than mechanically-accessed memories with similar capacities) and a somewhat slower internal shift rate than desired for some applications (of course, a slow internal data rate can be multiplexed to any desired in/out data rate if the access delays are not too large). The projections for 1985 are that many of these difficulties will have been overcome, particularly with the application of the bubble lattice file concept.

In Table 6 the 1985 projected characteristics of 10^{12} bit, new, mass memory technologies are compared. The user's choice of a mass memory technology will not be a simple decision. If one is primarily concerned with read/write updateable memories, there appear to be only two choices: semiconductor CCD's and magnetic bubbles. Of these two, semiconductor CCD's should provide somewhat faster access times and should be capable of high in/out data rates with less multiplexing, but it appears that system volume, weight, and power will be much greater (especially if some technique for producing very large capacity chips providing nonvolatile data storage is not yet available). Magnetic bubbles should be able to provide minimum size, weight, and power at moderate cost and may well be the optimum solution to many user needs. If archival data storage (write once and read many times; change media to rewrite) is needed, the choice may include electron beam and optical memories. If high speed access and high data rate are of prime importance, the electron beam memory has much to offer. If low media cost is of prime concern and slow access time is acceptable, then optical memories may be best.

5. CONCLUSION

We have accomplished the following in this section:

(1) We have derived a set of mass memory specifications from a realistic (but hypothetical) Air Force mission scenario.

(2) We have examined currently available mass memories to see if any of them can meet this specification

(3) We have projected four technologies that seem to have potential for meeting this specification in the next ten years.

TABLE 6

1985 PROJECTED CHARACTERISTICS 10^{12} BIT MASS MEMORIES

	Semiconductor	Optical	Electron Beam	Magnetic Bubble
Type	CCD	Bit by Bit	Ion Implant Write	Bubble Lattice File
Volatile/Non-Volatile	Volatile	Non-Volatile	Non-Volatile	Non-Volatile
Category	Read/Write	Archival	Archival	Read/Write
Cell Size	4 x 4 Micron	1 Micron	0.1 Microns	3 x 3 Micron
Chip Size	5 in Dia. Wafer	4 in x 4 in	3 in Diam. Wafers	2 in x 2 in Wafer
Chip Capacity	2 x 10^8 Bits	10^{10} Bits	10^{11} Bits	1.6 x 10^6 Bits
Module Capacity	2 x 10^8 Bits	10^{10} Bits	10^{11} Bits	3.2 x 10^8 Bits
Number Modules	5,000	100	10	3125
Access Time	0.1 to 20 mSec	1 Sec	30 uSec	80 uSec
Intrinsic Data Rate	10 Mbps	10 Mbps	10 Mbps	0.78 Mbps
System Volume	14 cu ft	27 cu ft	3.6 cu ft	1.4 cu ft
System Weight	1570 lbs	300 lbs	700 lbs	157 lbs
System Power	Standby 1 to 10 KW	2500 Watts	256 Watts	102 Watts
System Cost/Bit	0.1 to 1 m¢/Bit	0.06 m¢/Bit	0.02 m¢/Bit	0.25 m¢/Bit
System Cost(Total)	$1.0 to 10 Million	$0.6 Million	$0.2 Million	$2.5 Million

Based on the projections (3) above, we have shown that physically small solid state mass memories with at least 10^{12} bit capacity, access time less than 100 μSec, weight several hundred pounds or less, and power no greater than a few hundred watts, are feasible in the mid-1980's time period with several emerging technologies. These mass memories will be key components in real time airborne data processing and change detection systems. Integrated battlefield surveillance systems with real time data processing and change detection may well be combined with low bandwidth, secure communication links for direct, time shared command/control functions with multiple, low-cost strike vehicles to counter masses of heavy, mobile armor in future tactical warfare.

SECTION III

MEASUREMENTS ON MAGNETIC BUBBLE MATERIALS

1. INTRODUCTION

The apparent direction for future work on magnetic bubble memories is toward smaller magnetic bubbles. Magnetic bubble materials to support this work must be characterized for pertinent bubble properties as rapidly as possible. Current practice is to measure the magnetic field for bubble collapse (H coll) and the zero-field stripewidth (SW) in an optical microscope, to measure optical thickness (d opt = n t, where n is the optical index of refraction and t is the physical thickness), and to measure magnetic anisotropy in-plane/out-of-plane either in an M-H looper, in a microwave resonance apparatus, or in a special microscope capable of large in-plane magnetic fields[10]. This measurement is limited to bubbles that can be resolved in an optical microscope, that is, at least three micrometers in diameter. The thickness measurement must use an assumed (or measured, but the measurement is seldom made) optical index of refraction and requires a second piece of apparatus, an optical absorption spectrometer. The anisotropy measurement requires an in-plane/out-of-plane magnetic measurement and a third piece of apparatus. This set of measurements fully characterizes the static magnetic properties of bubble materials.

An improved technique for characterizing magnetic bubble materials has been described which uses diffraction from the random array of stripes at zero applied field and at the field for magnetization equals half the saturation value[11]. This "Laser Spatial Filtering" (LSF) technique eliminates the need for resolution of stripe edges and in principle, reduces the optical characterization to a diffration measurement, plus the thickness measurement and anisotropy measurement. Unfortunately, our experience is that as the bubble film gets thinner and thinner (for smaller and smaller bubbles), the diffracted intensity gets smaller and smaller and becomes unusable for films thinner than about three micrometers. Note that LSF characterization still requires three distinct pieces of apparatus for static characterization.

In an effort to simplify the measurement of static bubble materials properties, a new technique was investigated for microwave measurement of the magnetic fields for bubble collapse and stripout[12]. The bubble material would already be mounted for straightforward in-plane/out-of-plane magnetic anisotropy measurements in the same apparatus. It was felt that the LSF technique would be applicable to stripewidth and saturation magnetization measurements. The LSF was thought to be capable of defect mapping at that time, all in the same apparatus. Thickness was thought to be a quantity that could be derived magnetically from these measurements. Thus, complete static characterization could have been done with two pieces of apparatus, freeing the microscope for other work. Unfortunately, the LSF could not be made to determine saturation magnetization for films thinner than three micrometers. Additionally it has been learned that the LSF does not map defects other than physical scratches and dust on bubble films. This approach was abandoned as having too many elements not yielding useful data. Should an LSF technique for measuring saturation magnetization of small bubble films be found, or should an LSF technique for mapping only magnetic defects of small bubble films be found, the microwave - LSF combination would be worth reconsidering.

The best combination of techniques for measurement of static bubble properties was found to be zero-magnetization susceptibility (slope of the M-H curve at zero magnetization) times thickness, field for bubble stripout, and field for bubble collapse[13,14]. All these quantities can be measured in a suitable M-H looper. The anisotropy measurement can be made in a microwave resonance apparatus. From these quantities, all of the static bubble parameters can be derived. The major portion of this section will be devoted to this susceptibility/microwave combination technique. Further work is being done to investigate the feasibility of using in-plane/out-of-plane susceptibility to determine the anisotropy, to investigate the M-H looper "stickiness" (dependence on modulation field amplitude) for determining coercive field H_C, and to investigate the M-H looper frequency dependence for determining domain wall mobility. In other words two pieces of apparatus are needed for static characterization now, and the directions are evident for reducing this to a one piece apparatus which also perform the dynamic materials characterization.

2. MICROWAVE TECHNIQUE FOR CHARACTERIZING BUBBLE MATERIALS

During a systematic investigation of the ferromagnetic resonance absorption characteristics of magnetic bubble materials, a low-field change in microwave susceptibility was observed, as shown in Figure 2, in addition to the g=2 resonance. This susceptibility shift was found to be repeatable but was dependent on whether the field was decreasing or increasing. The shifts were found to be correlated with the bubble collapse field or stripe collapse field for increasing field sweep and the bubble strip-out field for decreasing field sweep[12].

At X-band frequency, a change in microwave susceptibility was observed at low fields for the magnetic field in the out-of-plane orientation. Operating the spectrometer in the derivative presentation mode, this change appeared as a peak with a distinctive nonresonance lineshape as shown in Figures 2-4, depending on the magnetic history of the bubble material sample. If the sample contained stripes, we obtained the spectrum shown in Figure 2 for either direction of field sweep (positive or negative field). If a large (5 KOe) in-plane magnetic field had been applied to the sample, then shut off, the metastable demagnetized state was a raft of magnetic bubbles throughout the sample. If the spectrum was then observed with increasing field sweep followed by decreasing field sweep, the spectra of Figures 3 and 4 were obtained. Figure 3 represents bubble collapse (up-field sweep) followed by "stripe stripout" (down - field sweep) while Figure 4 presents the case where bubble size increases with increasing field with "negative bubble" collapse (up-field sweep) followed by "stripe stripout" (down-field sweep). We observe that the shape and position of the susceptibility change with decreasing field sweep is indistinguishable for the three cases and also if the field was increased (in the direction such that bubbles decreased in size with increasing field) to within the bubble stability range, then decreased past the bubble stripout field. Put another way, we observe that bubble stripout, stripe "stripout", and "negative bubble" stripout are indistinguishable in position and lineshape when measured by low-field microwave susceptibility changes. On the other hand, bubble collapse, stripe collapse, and "negative bubble" collapse have distinctive lineshapes and occur at different applied magnetic fields. We observed similar

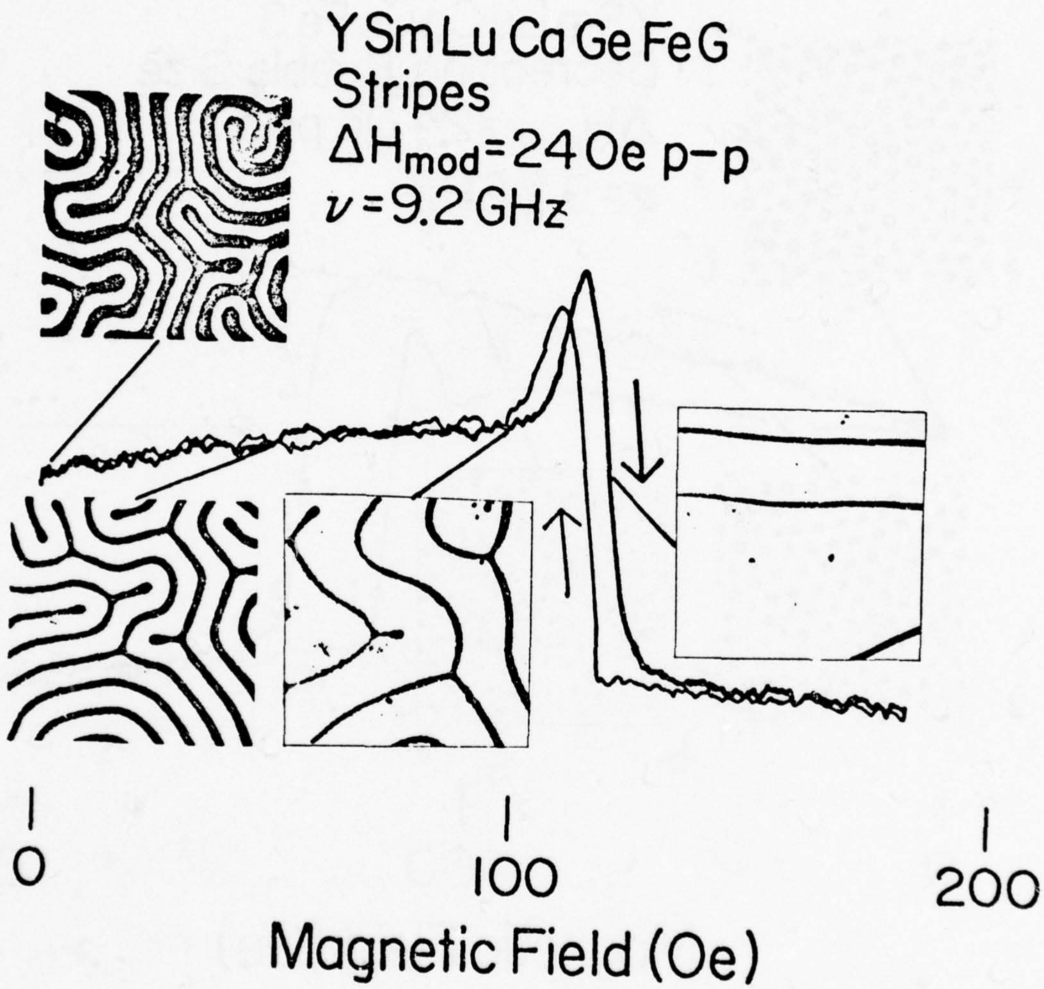

Figure 2. Low-Field Microwave Spectrum of Stripe Collapse and Stripout

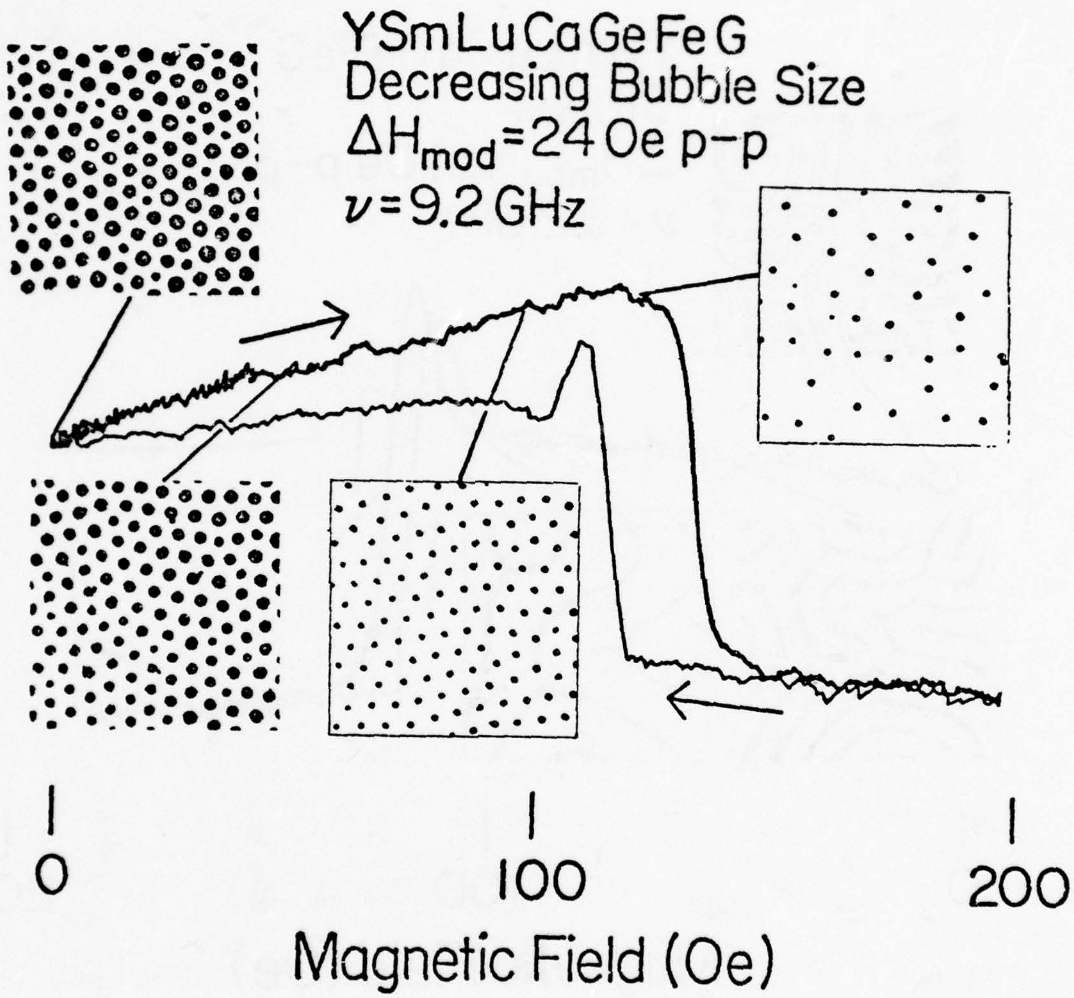

Figure 3. Low-Field Microwave Spectrum of Bubble Raft Collapse and Stripout

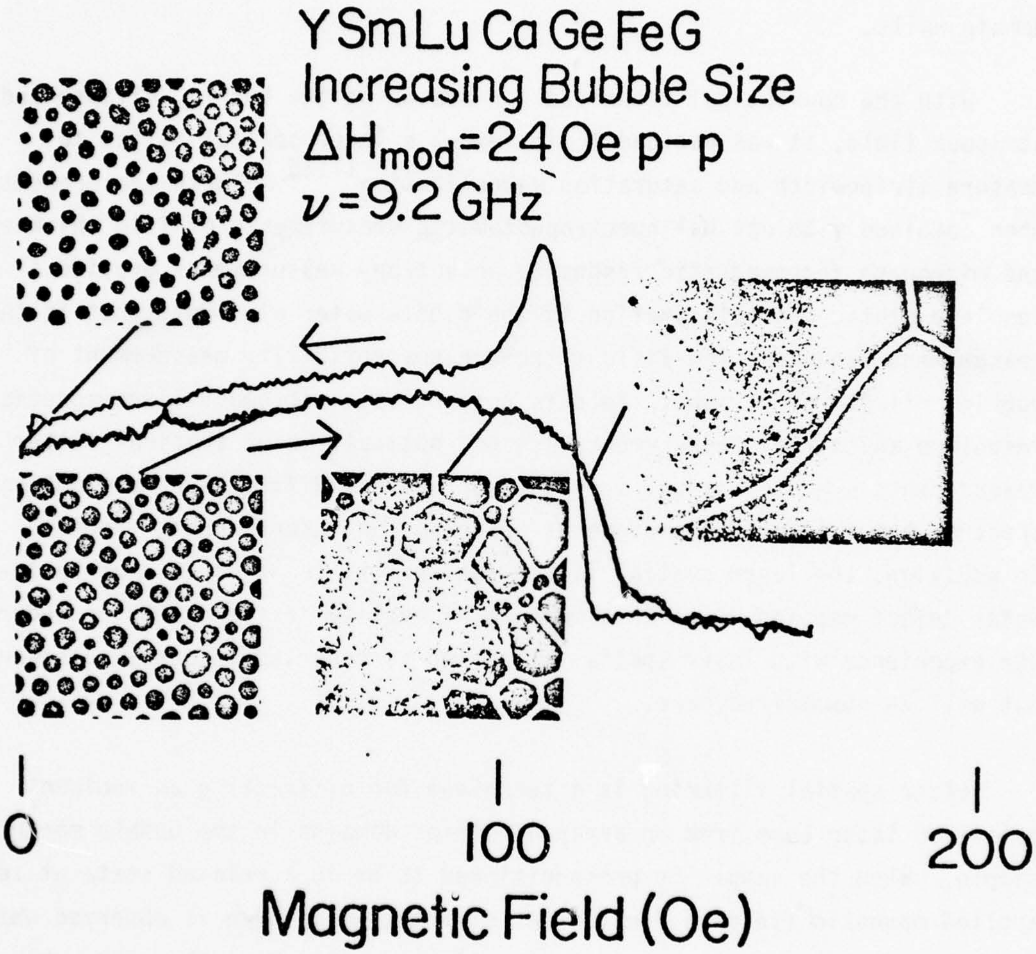

Figure 4. Low-Field Microwave Spectrum of "Negative Bubble" Collapse and Stripout

susceptibility changes at 10, 15, 20 MHz but did not observe any low-field susceptibility changes at 24 GHz. The mechanism responsible for the susceptibility change at microwave frequencies is, as yet, incompletely understood but is felt to be due to a spinwave scattering from the magnetic domain walls.

With the non-optical technique for measuring the bubble collapse and stripout field, it was decided to implement a laser spatial filter to measure stripewidth and saturation magnetization[11,15]. These measurements, when combined with optical spectrophotometer measurements of film thickness and microwave ferromagnetic resonance anisotropy measurements provide a complete static characterization of the bubble material. Note that in this measurement sequence, low-field microwave susceptibility measurement of bubble collapse or stripout field is non-optical, microwave ferromagnetic resonance anisotropy measurements are non-optical, laser spatical filter measurements are optical but are based on optical diffraction, and optical spectrometer thickness measurements are based on interference effects. In addition, the laser spatial filter was thought to be capable of whole-wafer defect mapping which is a measure of quality in the growth procedure. Our experience with laser spatial filtering is reported in detail elsewhere,[15] but will be summarized here.

Laser spatial filtering is a technique for diffracting an incident polarized laser beam from an array of stripe domains in the bubble material sample. When the sample is preconditioned to be in a relaxed state at zero applied magnetic field, a first order diffraction pattern is observed which can be used to determine the zero-magnetization stripe-width. From this stripewidth, the position of the second order diffraction can be calculated. If the second order pattern is observed, it reaches a maximum in intensity when the sample is magnetized to half of the saturation value. The magnetic field to achieve this half-saturation value is noted and can be used to determine the saturation magnetization. When we sought to implement the laser spatial filtering measurement, we found severe difficulty with pre-conditioning the sample to achieve a reproducible and believable zero-magnetization state with four or five micrometer thickness bubble material.

This was partially solved by applying a combined ac and dc field with dc value exceeding the collapse field, then decreasing the dc field to zero. This procedure allowed us to determine the zero-field stripewidth with about 2% reproducibility. The spatial filter was then moved to a calculated location and the second-order diffraction pattern focused into the silicon PIN detector.

The dc magnetic field on the sample was increased until the intensity was a maximum. For four or five micrometer thick materials, this procedure was reproducible to within 10%. The materials which are of real interest to this effort are one or two micrometers thick and the next step was to attempt to measure them. We found that the first order diffraction intensity was reduced by a factor of about ten, which decreased the reproducibility in the measurement of zero-field stripewidth to about 10%. Repeated attempts to observe the second-order diffraction were completely unsuccessful due to extremely low intensity. It was finally concluded that laser spatial filtering, in its present state, cannot be used for characterizing bubble materials thinner than about three micrometers, primarily due to low intensity. At a late stage in this investigation it was learned that the laser spatial filter, in its present state, cannot be used to map magnetic defects because physical scratches and dust on the surface completely obscure any magnetic defects that might be present.[15]

The microwave/LSF approach to characterizing one and two micrometer thick magnetic bubble materials was finally abandoned, not because the microwave measurement failed, but because the laser spatial filtering technique had too many components which were not yielding useful data on small bubble materials. The original hope, that zero-field stripewidth and saturation magnetization could be used to derive an effective magnetic thickness, was not carried further due to the apparent impossibility of obtaining reliable experimental data. Before the approach was abandoned, a computer program was written to derive the static magnetic bubble parameters from bubble collapse field, zero-field stripewidth, and physical thickness using the theory of Thiele.[16] This computer program is reproduced in the Appendix with instructions for use and sample calculations. This program can also derive the static magnetic bubble parameters from laser

spatial filter data: field for magnetization equal to half the saturation value, zero-field stripewidth, and physical thickness. In this computer program, the exact theory of Thiele[16] was used, rather than the commonly applied approximation of Callen and Joseph,[17] to explore the accuracy of the approximate calculation for small bubble materials. Certainly the exact theory program runs very rapidly and does not require much computer memory; the advantages of the approximate theory seem very small. In fact, even the exact theory (which does not include the effects of anisotropy) seems to introduce errors into the calculation of materials parameters[15] and further approximations may worsen the errors.

3. SUSCEPTIBILITY TECHNIQUES FOR CHARACTERIZING BUBBLE MATERIALS

A technique for bubble materials characterization is described which uses low frequency magnetic susceptibility and bubble collapse and stripout measurements. This method is presented as an alternative to the microwave and laser spatial filtering technique. It can be automated and, since domains are not detected optically, there are no resolution problems. The technique can also be used on opaque magnetic metal films.

The low frequency susceptibility characterization determines the zero-magnetization stripwidth, characteric length, saturation magnetization, and thickness from the zero-magnetization susceptibility $\left.\frac{dM}{dH}\right|_{M=0} = X_o$, the bubble stripout field H_{so}, and the bubble collapse H_{coll}. The thickness is a magnetically determined effective value, which could differ from the physical thickness due to dead layers or other nonmagnetic layers deposited. Henry has pointed out that the difference between magnetic thickness and optical thickness will become significant for films below one micrometer thickness.

The theory of Kooy and Enz[18] leads to the following two equations which interrelate the static properties of bubble domain materials:

$$0 = \frac{4\pi M - H}{4\pi M_S} + \frac{d}{\pi^2 h} \sum_{n=1}^{\infty} \frac{1}{n^2} \sin\{n\pi(1 + \frac{M}{M_S})\} \{1 - \exp(-\frac{2\pi nh}{d})\} \quad (1)$$

$$\frac{\ell}{h} = \frac{d^2}{\pi^3 h^2} \sum_{n=1}^{\infty} \sin^2\{\frac{n\pi}{2}(1 + \frac{M}{M_S})\} \{1 - (1 + \frac{2\pi nh}{d})\exp(-\frac{2\pi nh}{d})\} \quad (2)$$

Here M_s is the saturation magnetization, M is the average magnetization of the film, d is the domain period, h is the film thickness, and H is a magnetic field applied perpendicular to the film's surface. The derived quantity ℓ is the characteristic length, a materials constant.

The magnetic susceptibility $\frac{dM}{dH} = X$ can be obtained by solving equations (1) and (2) numerically and evaluation the slopes of the resulting M vs. H curves. However, our interest is only in the zero-magnetization susceptibility X_o, and the corresponding value of $\frac{\ell}{h}$. After some algebraic manipulations, the following equations are obtained for M = 0:

$$4\pi X_o = \{1 + \frac{2w}{\pi h} \sum_{n=1}^{\infty} \frac{1}{n}(-1)^n \; [1 - \exp(-\frac{n\pi h}{w})]\}^{-1} \quad (3)$$

and

$$\frac{\ell}{h} = \frac{4w^2}{\pi^3 h^2} \sum_{n(odd)}^{\infty} \frac{1}{n^3} \; [1 - (1 + \frac{n\pi h}{w} \exp(-\frac{n\pi h}{w})] \quad (4)$$

where w is the zero-magnetization stripewidth.

The calculated values SW/h, $4\pi X_o$, $\frac{H_{coll}}{4\pi M_s}$, $\frac{H_{so}}{4\pi M_s}$, and H_{so}/H_{coll} are plotted as functions of $\frac{\ell}{h}$ in Figures 5 and 6. A computerized analysis procedure using tables of values of the quantities in Figures 5 and 6 has been written to analyze experimental data and calculate the magnetic bubble materials parameters. This program is listed in the Appendix with examples of its use. At least three out-out-plane experimental quantities must be measured, including one each magnetic and linear quantities. Here zero-magnetization susceptibility $4\pi X_o$ is considered a magnetic quantity (but an additional magnetic quantity must be measured to completely characterize the material), while susceptibility times thickness $4\pi X_o h$ (the actual experimental quantity) is considered a linear parameter. This program calculates a table of bubble diameters vs applied field if characterization is complete, and will also perform theoretical calculations of all the other parameters if a complete set of materials parameters is input. This program is listed in the Appendix together with instructions for use and sample calculations.

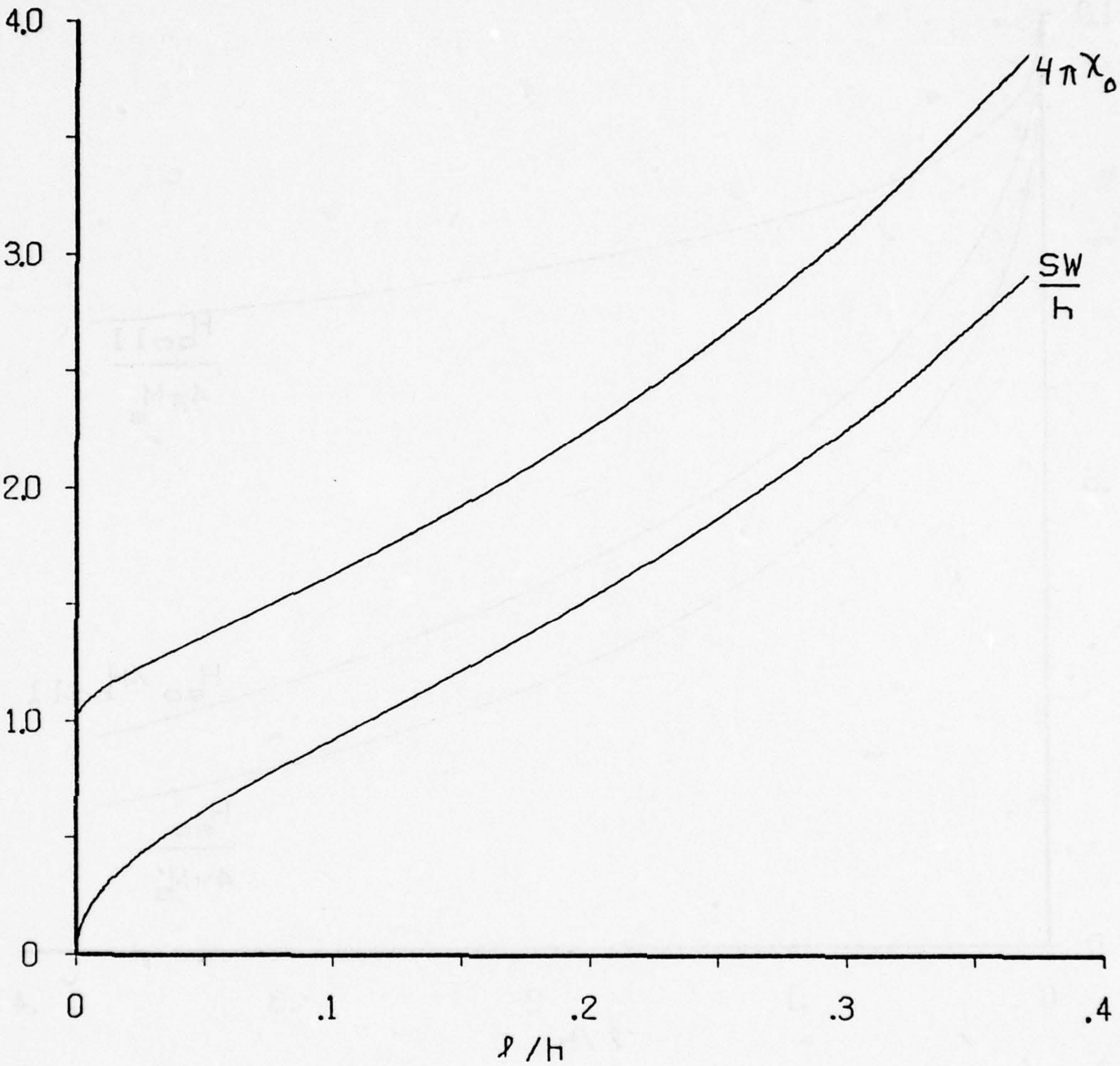

Figure 5. Plot of Rationalized Zero-Magnetization Susceptibility ($4\pi X_0$) and Zero-Magnetization Stripewidth by Thickness (SW/h) Against Characteristic Length by Thickness (ℓ/h)

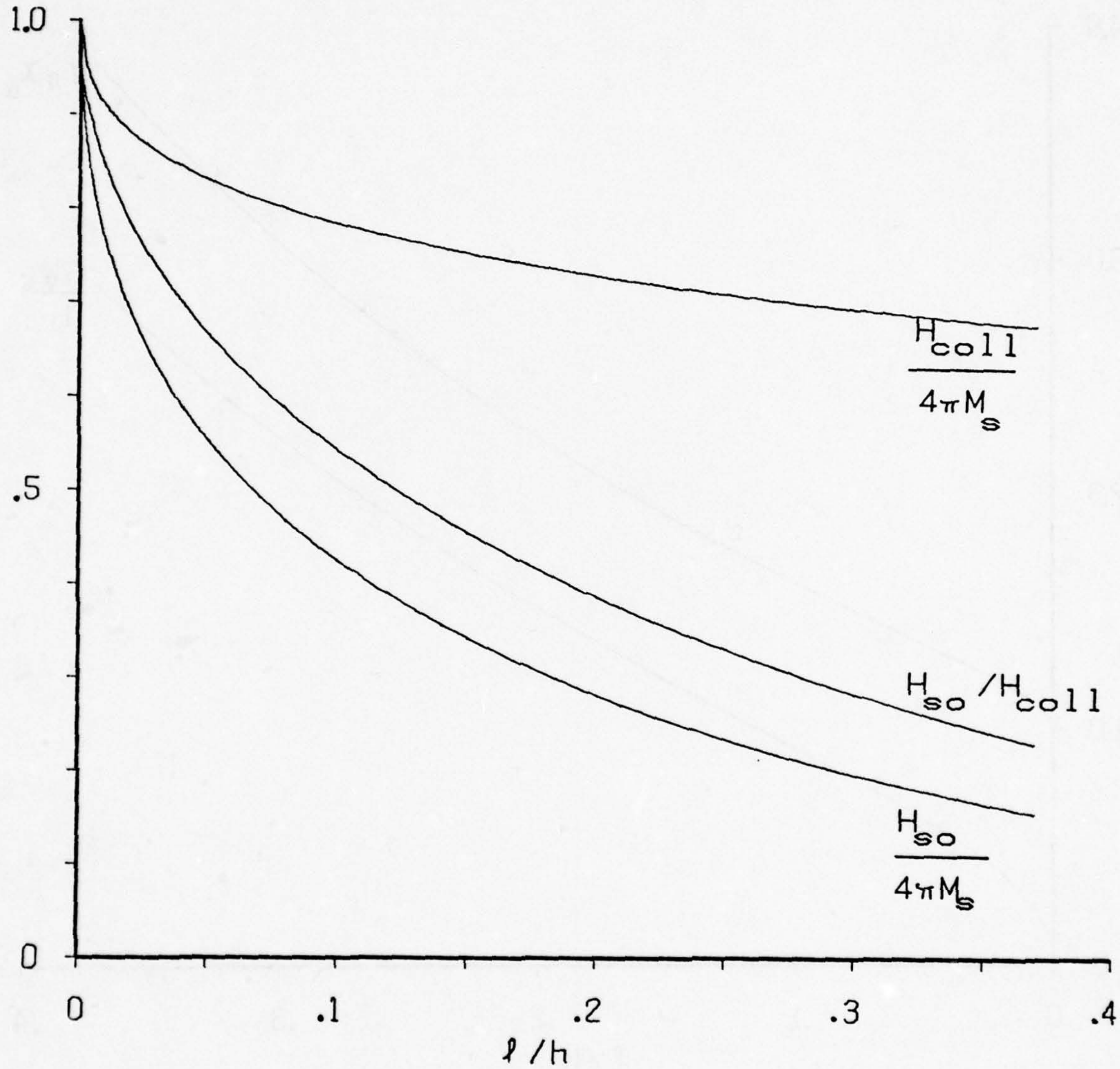

Figure 6. Plot of Bubble Collapse Field by Saturation Magnetization, Bubble Stripout Field by Saturation Magnetization, and Bubble Stripout Field by Bubble Collapse Field Against Characteristic Length by Thickness

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

Program BUBCHAR is written in CDC FORTRAN EXTENDED, but an effort has been made to use FORTRAN IV coding wherever possible. Thus the program should run on most computers with few changes.

There appears to be small advantage to using the Callen and Josephs approximation[17] in bubble materials calculations. The ratios in the data statements were computed from Thiele theory[16] or Kooy and Enz theory[18]. In fact, two instructions are included to unraval the saturation magnetization calculated using the Callen and Josephs approximation, then recalculate the materials parameters according to Thiele theory[16]. The major inaccuracy in analysis is the ad hoc introduction of anisotropy, after calculating all other parameters assuming that the material is isotropic.

The computer program BUBCHAR is listed in the Appendix following, and if the author is sent a blank half-inch magnetic computer tape, he will write card images of the program on the tape and return it. Be sure to specify density, number of tracks, and any standards or conventions that would make the tape easier to use. As a poor alternative, the author can provide a card copy of the program (Be sure to specify the keypunch standard needed. Only "029" keypunch standard cards can be interpreted at this facility).

APPENDIX

A. INTRODUCTION

A CDC Fortran Extended computer program has been written primarily to analyze sets of experimental data and calculate static bubble materials parameters. Three out-of-plane measurements are needed, plus one in-plane measurement to specify the anisotropy. The computer then calculates interpolations and ratios analogously to the graphical procedure described by Thiele[16] to determine the bubble materials static parameters. The program will also accept a complete set of bubble materials parameters and calculate values of all the experimental and materials parameters. If a sufficient set of out-of-plane parameters is input, the program calculates a set of stable bubble diameters and applied field values. If no in-plane information is input, the program simply does not calculate anisotropy field, anisotropy energy density or q-factor.

B. INSTRUCTIONS FOR INPUT

Program BUBCHAR is written to accept data cards consisting of an instruction (columns 1-10) followed by a number (containing a decimal point) in columns 11-20. Non-instruction comment cards may be used without restrictions. The permissible instructions are listed and defined in Table A1. As soon as three out-of-plane parameters are input (including at least one each magnetic and linear quantities), the program calculates all the other quantities from Thiele Theory[16] or Kooy and Enz Theory[18]. An in-plane parameter may be input anywhere in the data deck or may be omitted.

TABLE A-1

INSTRUCTIONS FOR INPUT DATA: PROGRAM BUBCHAR

Instruction	Classification	Definition
HC	out of plane magnetic	bubble collapse field H_c (Oe)
HCOLL	"	"
HCOLLAPSE	"	"
HSO	"	bubble stripe out field H_{so} (Oe)
HSC	"	"
HSTRIPEOUT	"	"
T	out of plane linear	bubble material thickness h (microns)
THICK	"	"
THICKNESS	"	"
H	"	"
XØH	"	zero-magnetization susceptibility times thickness
CHIØH	"	"
SW	"	zero-magnetization stripewidth (microns)
S	"	"
STRIPEWIDT	"	"
STRIPWIDTH	"	"
MAG	out of plane magnetic	saturation magnetization (gauss)
MS	"	"
4.PI.MS	"	"
M	"	"
L	out of plane linear	characteristic length ℓ (microns)
CHARLENGTH	"	"
XØ	out of plane magnetic	zero-magnetization susceptibility (Gauss/Oe)
CHIØ	"	"
Q	in plane magnetic	anisotropy quality factor
HU	"	anisotropy field (Oe)
HA	"	"
HK	"	"
KU	"	anisotropy energy density (ergs/cm^3)
4.PI.M	out of plane magnetic	saturation magnetization calculated on Callen & Joseph approx
CJM	"	"
H(1/2)	"	field for half-saturation magnetization (Oe)
H1/2	"	"
H12	"	"
HHALF	"	"
LABEL	Alphanumeric identifier (up to 70 characters)	
TITLE	"	
Any Other	Comments (printed as they are punched) Do not use just before an in-plane card.	

C. EXAMPLES OF USE OF BUBCHAR

1. Example 1:

   Input: H
   SW
   HCOLL
   HK

   Output: Fig A-1

2. Example 2:

   Input: H
   CHIØH
   HSO
   HK

   Output: Fig A-2

3. Example 3:

   Input: H
   4.PI.MS
   L
   Q

   Output: Fig A-3

4. Example 4:

   Input: H
   XØ
   SW

   Output: Fig A-4

D. Listing of Program BUBCHAR

```
PROGRAM BUBCHAR


H                     2.40000
SW                    1.80000
HCOLL               409.00000


H =  .240000E+01, L =  .169471E+00, CHIO =  .147861E+01, SW =  .180000E+01
4.PI.MS =  .673001E+03, HS =  .330122E+03, HC =  .409000E+03, BULK WALL ENERGY =  .610826E+00
H1/2 (FIELD FOR HALF-SATURATION MAGNETIZATION) =  .219570E+03

-------------------------------------------------------------
 BUBBLE DIAMETER (MICRONS)           APPLIED FIELD (OE)
-------------------------------------------------------------
           1.12                            406.52
           1.29                            400.56
           1.46                            392.75
           1.63                            384.06
           1.80                            374.93
           1.97                            365.66
           2.14                            356.44
           2.30                            347.41
           2.47                            338.62
-------------------------------------------------------------

 BUBBLE COLLAPSE DIAMETER =      .95  MICRONS
 BUBBLE COLLAPSE FIELD    =   409.00  OERSTEDS
 BUBBLE RUNOUT DIAMETER   =     2.64  MICRONS
 BUBBLE RUNOUT FIELD      =   330.12  OERSTEDS



HK                 4172.00000



 MAXIMUM TWIST ANGLE.............= 88.4342   DEGREES    ( 1.54  RAD.)
 DOMAIN WALL ENERGY..............=    .585885E+00      ERGS/SQ.CM.
 WALL THICKNESS..................=    .448062E-01   MICRONS
 Q =       6.193, KU =  .111717E+06, HK =  .417200E+04, AND EXCHANGE CONSTANT =  .208735E-06
```

Figure A-1 Output from computer program BUBCHAR for Example 1. This calculation is for the standard characterization measurements with thickness H = 2.40 micrometers, zero-magnetization stripewidth SW = 1.80 micrometers, bubble collapse field HCOLL = 409.0 Oersteds, and anisotropy field HK = 4172.0 Oersteds.

```
PROGRAM BUBCHAR


H                       2.40000
CHIOH                   3.30000
HSO                   299.60000


H =  .240000E+01, L =  .122080E+00, CHI0 =  .137500E+01, SW =  .149772E+01
4.PI.MS =  .545355E+03, HS =  .299600E+03, HC =  .361636E+03, BULK WALL ENERGY =  .289567E+00
H1/2 (FIELD FOR HALF-SATURATION MAGNETIZATION) =  .193128E+03

------------------------------------------------------------
 BUBBLE DIAMETER (MICRONS)             APPLIED FIELD (OE)
------------------------------------------------------------
              .92                          359.79
             1.06                          355.34
             1.20                          349.42
             1.34                          342.65
             1.48                          335.48
             1.61                          328.18
             1.75                          320.87
             1.89                          313.63
             2.03                          306.53
------------------------------------------------------------

 BUBBLE COLLAPSE DIAMETER =      .78  MICRONS
 BUBBLE COLLAPSE FIELD    =   361.64  OERSTEDS
 BUBBLE RUNOUT DIAMETER   =     2.17  MICRONS
 BUBBLE RUNOUT FIELD      =   299.60  OERSTEDS



HK                   1273.00000


 MAXIMUM TWIST ANGLE..............= 87.3025   DEGREES    ( 1.52  RAD.)
 DOMAIN WALL ENERGY...............=  .262602E+00        ERGS/SQ.CM.
 WALL THICKNESS...................=  .908648E-01   MICRONS
 Q =       2.332, KU =  .276532E+05, HK =  .127300E+04, AND EXCHANGE CONSTANT =  .189510E-06
```

Figure A-2 Output from computer program BUBCHAR for Example 2. This calculation is for the suggested optimum characterization measurements with the thickness H = 2.40 micrometers, zero-magnetization susceptibility times thickness CHIOH = 3.30 EMU-micrometers, bubble stripout field HSO = 299.6 Oersteds, and anisotropy field HK = 1273. Oersteds.

```
PROGRAM BUBCHAR


H                    3.10000
4.PI.MS            537.50000
L                     .09740


H =  .310000E+01, L =  .974000E-01, CHIO =  .127063E+01, SW =  .149998E+01
4.PI.MS =  .537500E+03, HS =  .336132E+03, HC =  .392624E+03, BULK WALL ENERGY =  .223927E+00
H1/2 (FIELD FOR HALF-SATURATION MAGNETIZATION) =  .207544E+03

-------------------------------------------------------
BUBBLE DIAMETER (MICRONS)            APPLIED FIELD (OE)
-------------------------------------------------------
           .91                            390.91
          1.04                            387.01
          1.18                            381.83
          1.32                            375.89
          1.45                            369.49
          1.59                            362.84
          1.73                            356.09
          1.86                            349.34
          2.00                            342.69
-------------------------------------------------------

BUBBLE COLLAPSE DIAMETER =      .77  MICRONS
BUBBLE COLLAPSE FIELD    =   392.64  OERSTEDS
BUBBLE RUNOUT DIAMETER   =     2.14  MICRONS
BUBBLE RUNOUT FIELD      =   336.15  OERSTEDS



Q                    3.20000


MAXIMUM TWIST ANGLE.............=  88.5220   DEGREES    ( 1.55  RAD.)
DOMAIN WALL ENERGY..............=   .214858E+00      ERGS/SQ.CM.
WALL THICKNESS..................=   .498552E-01   MICRONS
Q =     3.200, KU =  .367847E+05, HK =  .172000E+04, AND EXCHANGE CONSTANT =  .851971E-07
```

Figure A-3 Output from computer program BUBCHAR for Example 3. This calculation is a theoretical calculation for a bubble material with thickness H = 3.10 micrometers, rationalized saturation magnetization 4.PI.MS = 537.5 Gauss, characteristic length L = 0.0974 micrometers, and anisotropy quality factor Q = 3.2.

```
  PROGRAM BUBCHAR

H                     1.50000
X0                    1.40900
SW                    1.00000

X0 WAS THE ONLY MAGNETIC PARAMETER INPUT
X0 =  .140907E+01, H =  .150000E+01, SW =  .100000E+01, AND L =  .860438E-01.
ALL THAT CAN BE SAID ABOUT THE OTHER MAGNETIC PARAMETERS IS
HC/4.PI.MS =  .643196E+00 AND HS/4.PI.MS =  .527942E+00.
```

Figure A-4 Output from computer program BUBCHAR for Example 4. Note that the characterization is incomplete, as zero-magnetization susceptibility (or zero-magnetization susceptibility times thickness) is insufficient to specify the magnetic parameters of a material. Input was thickness H = 1.50 micrometers, zero-magnetization susceptibility X0 = 1.409 EMU, and zero-magnetization stripewidth SW = 1.00 micrometers.

```
      PROGRAM BUBCHAR(INPUT=101B,OUTPUT=101B,TAPE5=INPUT,TAPE6=OUTPUT)
      DIMENSION PHI1(120), EDASH(120),RATIO(120)
      DIMENSION HCBYMS(40),HCBYHS(40)
      DIMENSION HSBYMS(40),WOVH(40),CHI0(40),LABEL(8)
      DIMENSION INSTR(35),CARD(8),KMAG(2),KLEN(2),DI(56)
      DIMENSION HHALF(40)
      REAL L,MS,LOH,LOVH(40),KU
      COMMON /AA/ Q
      DATA DI/56*1./,LABEL/8*1H /
C
C        I =          1       2           3       4       5           6     7
C
      DATA INSTR/"HC","HCOLL","HCOLLAPSE","HSO","HSC","HSTRIPOUT","T",
C
C          8              9  10      11          12    13  14            15
C
     1 "THICK","THICKNESS","H","XOH","CHIOH","SW","S","STRIPEWIDT",
C
C                 16      17   18          19   20   21           22     23
C
     2 "STRIPWIDTH","MAG","MS","4.PI.MS","M","L","CHARLENGTH","X0",
C
C            24   25   26    27    28    29        30     31         32       33
C
     3 "CHIO","Q","HU","HA","HK","KU","4.PI.M","CJM","H(1/2)","H1/2",
C
C          34       35
     4 "H12","HHALF"/
C
     0DATA PHI1/6*0.,.01,.03,.05,.07,.1,.4,.58,.9,1.14,1.26,1.33,1.375,
     1 1.4,1.42,1.435,1.48,1.485,1.5,1.52,1.525,1.531,1.537,1.54,1.545,
     2 6*0.,.01,.03,.05,.07,.08,.35,.5,.865,1.08,1.23,1.31,
     3 1.35,1.38,1.41,1.42,1.47,1.485,1.5,1.52,1.525,1.531,1.537,1.54,
     4 1.545,6*0.,.01,.03,.04,.065,.07,.27,.4,.76,1.,1.14,1.26,1.32,
     5 1.35,1.4,1.41,1.48,1.485,1.5,1.52,1.525,1.531,1.537,1.54
     6 ,1.545,6*0.,.001,.009,.01,.02,.03,.13,.2,.42, 65,.84,.99,1.1,
     7 1.2,1.25,1.3,1.45,1.47,1.5,1.52,1.525,1.531,1 537,1.54,1.545/
     0DATA EDASH/.825,.94,.98,1.,1.2,1.24,1.28,1.32,1.36,1.4,1.45,1.5,
     1 1.5,1.45,1.4,1.37,1.372,1.4,1.418,1.44,1.47,1.59,1.6,1.48,1.52,
     2 1.56,1.58,1.8,1.82,1.825,1.08,1.18,1.22,1.28,1.34,1.4,1.43,1.47,
     3 1.5,1.52,1.55,1.565,1.58,1.52,1.48,1.44,1.43,1.45,1.46,1.48,1.52,
     4  1.61,1.61,1.49,1.53,1.57,1.59,1.81,1.83,1.835,1.5,1.525,1.55,
     5 1.575,1.6,1.625,1.65,1.675,1.7,1.72,1.74,1.75,1.749,1.71,1.7,
     6 1.625,1.632,1.65,1.67,1.675,1.69,1.72,1.75,1.79,1.805,1.82,
     7 1.835,1.842,1.85,1.855,1.83,1.84,1.85,1.855,1 66,1.87,1 88,1.9,
     8 1.903,1.907,1.91,1.915,1.92,1.91,1.9,1.895,1.894,1.89,1.885,1.883
     9 ,1.88,1.885,1.89,1.895,1.9,1.905,1.91,1.913,1 916,1.919/
     0DATA RATIO/.35,.365,.375,.41,.44,.465,.49,.52,.54,.56,.588,.7,
     1 .72,.755,.74,.725,.78,.725,.73,.74,.75,.795,.8,.84,.86, 87,.88
     2 ,.89,.895,.9,.48,.49,.5,.527,.55,.565,.59,.618,.63,.645,.66,
     3 .75,.76,.778,.755,.74,.738,.738,.746,.75,.76,.805,.81,.85,.87,
     4 .88,.89,.9,.905,.91,.725,.73,.735,.75,.76,.78,.79,.797, 8,.808,
     5 .815,.85,.86,.86,.85,.83,.82,.82,.82,.82,.83,.845,.855,.88,.9,
     6 .908,.92,.928,.928,.929,.903,.909,.912,.915,.918,.92,.928,.93,
     7 .935,.938,.94,.95,.955,.96,.96,.95,.945,.943,.93,.93,.93,.92,.92,
     8 .92,.94,.945,.95,.955,.957,.959/
      DATA PI4/12.5663702/
```

```
 DATA (LOVH(I),I=1,40)/0.,.001,.005,.01,.02,.03,.04,.05,.06,.07,     BUBCH 58
1 .08,.09,.1,.11,.12,.13,.14,.15,.16,.17,.18,.19,.2,.21,.22,.23,     BUBCH 59
2 .24,.25,.26,.27,.28,.29,.3,.31,.32,.33,.34,.35,.36,.37/            BUBCH 60
 DATA (WOVH(I),I=1,40)/ .000000E+00, .858544E-01, .191964E+00,       BUBCH 61
1  .271493E+00, .384400E+00, .472441E+00, .548706E+00, .618242E+00,BUBCH 62
2  .683589E+00, .746226E+00, .807092E+00, .866843E+00, .925947E+00,BUBCH 63
3  .984762E+00, .104357E+01, .110261E+01, .116205E+01, .122209E+01,BUBCH 64
4  .128284E+01, .134446E+01, .140705E+01, .147072E+01, .153558E+01,BUBCH 65
5  .160172E+01, .166925E+01, .173825E+01, .180881E+01, .188102E+01,BUBCH 66
6  .195495E+01, .203072E+01, .210839E+01, .218806E+01, .226982E+01,BUBCH 67
7  .235375E+01, .243994E+01, .252849E+01, .262948E+01, .272302E+01,BUBCH 68
8  .281921E+01, .291812E+01/                                        BUBCH 69
 DATA (CHIO(I),I=1,40)/ .100000E+01, .103937E+01, .109252E+01,       BUBCH 70
1  .113607E+01, .120412E+01, .126268E+01, .131741E+01, .137044E+01,BUBCH 71
2  .142289E+01, .147538E+01, .152832E+01, .158202E+01, .163668E+01,BUBCH 72
3  .169249E+01, .174959E+01, .180809E+01, .186811E+01, .192977E+01,BUBCH 73
4  .199314E+01, .205831E+01, .212538E+01, .219441E+01, .226552E+01,BUBCH 74
5  .233876E+01, .241423E+01, .249201E+01, .257217E+01, .265482E+01,BUBCH 75
6  .274002E+01, .282788E+01, .291847E+01, .301190E+01, .310825E+01,BUBCH 76
7  .320765E+01, .331015E+01, .341588E+01, .352494E+01, .363744E+01,BUBCH 77
8  .375348E+01, .387319E+01/                                        BUBCH 78
 DATA (HSBYMS(I),I=1,40)/ .100000E+01, .913816E+00, .827575E+00,     BUBCH 79
1  .767021E+00, .688159E+00, .632214E+00, .588324E+00, .551689E+00,BUBCH 80
2  .519989E+00, .492127E+00, .467205E+00, .444614E+00, .423992E+00,BUBCH 81
3  .404978E+00, .387335E+00, .370973E+00, .355626E+00, .341221E+00,BUBCH 82
4  .327698E+00, .314934E+00, .302872E+00, .291400E+00, .280539E+00,BUBCH 83
5  .270227E+00, .260365E+00, .250982E+00, .241974E+00, .233436E+00,BUBCH 84
6  .225230E+00, .217388E+00, .209840E+00, .202612E+00, .195706E+00,BUBCH 85
7  .189074E+00, .182683E+00, .176523E+00, .170612E+00, .164945E+00,BUBCH 86
8  .159475E+00, .154195E+00/                                        BUBCH 87
 DATA (HCBYMS(I),I=1,40)/0.100000E+01, .932890E+00, .888869E+00,     BUBCH 88
1  .844016E+00, .782610E+00, .736317E+00, .698073E+00, .665064E+00,BUBCH 89
2  .635771E+00, .609272E+00, .585003E+00, .562550E+00, .541623E+00,BUBCH 90
3  .521995E+00, .503513E+00, .486055E+00, .469540E+00, .453861E+00,BUBCH 91
4  .438925E+00, .424669E+00, .411033E+00, .397963E+00, .385417E+00,BUBCH 92
5  .373357E+00, .361754E+00, .350586E+00, .339831E+00, .329454E+00,BUBCH 93
6  .319431E+00, .309743E+00, .300382E+00, .291345E+00, .282513E+00,BUBCH 94
7  .274168E+00, .266002E+00, .258094E+00, .250430E+00, .242999E+00,BUBCH 95
8  .235789E+00, .228788E+00/                                        BUBCH 96
 DATA (HCBYHS(I),I=1,40)/0.100000E+01, .102087E+01, .107406E+01,     BUBCH 97
1  .110038E+01, .113725E+01, .116466E+01, .118655E+01, .120551E+01,BUBCH 98
2  .122266E+01, .123804E+01, .125213E+01, .126526E+01, .127744E+01,BUBCH 99
3  .128895E+01, .129994E+01, .131022E+01, .132032E+01, .133011E+01,BUBCH100
4  .133942E+01, .134844E+01, .135712E+01, .136569E+01, .137384E+01,BUBCH101
5  .138164E+01, .138941E+01, .139686E+01, .140441E+01, .141132E+01,BUBCH102
6  .141824E+01, .142484E+01, .143148E+01, .143795E+01, .144407E+01,BUBCH103
7  .145006E+01, .145608E+01, .146210E+01, .146783E+01, .147321E+01,BUBCH104
8  .147853E+01, .148376E+01/                                        BUBCH105
 DATA (HHALF(I),I=1,40)/ .498618E+00. .479843E+00, .454930E+00,      BUBCH106
1  .436243E+00, .409608E+00, .388816E+00, .370984E+00, .355055E+00,BUBCH107
2  .340511E+00, .327050E+00, .314480E+00, .302668E+00, .291515E+00,BUBCH108
3  .280948E+00, .270907E+00, .261344E+00, .252218E+00, .243496E+00,BUBCH109
4  .235148E+00, .227150E+00, .219478E+00, .212113E+00, .205037E+00,BUBCH110
5  .198234E+00, .191689E+00, .185388E+00, .179320E+00, .173473E+00,BUBCH111
6  .167838E+00, .162403E+00, .157160E+00, .152100E+00, .147217E+00,BUBCH112
7  .142502E+00, .137947E+00, .133549E+00, .129238E+00, .125191E+00,BUBCH113
8  .121221E+00, .117383E+00/                                        BUBCH114
```

```
    9 MS=0.
   10 CONTINUE
      IF(MS.EQ.0.) WRITE(6,5000)
 5000 FORMAT("1  PROGRAM BUBCHAR"//)
      NMAG=0
      NLEN=0
      KIPM=0
    1 READ(5,960) INS
  960 FORMAT(A10)
      IF(EOF(5)) 100,15
   15 CONTINUE
      BACKSPACE 5
      DO 2 I=1,35
      IF(INSTR(I).EQ.INS) GO TO 3
    2 CONTINUE
      READ(5,961) CARD
  961 FORMAT(8A10)
      IF(EOF(5)) 100,25
   25 CONTINUE
      WRITE(6,1060) CARD
 1060 FORMAT(1X,8A10)
      IF(INS.EQ."TITLE".OR.INS.EQ."LABEL") GO TO 85
      GO TO 1
    3 READ(5,962) INS,A1
  962 FORMAT(A10,F10.0)
      IF(EOF(5)) 100,35
   35 CONTINUE
      WRITE(6,1070) INS,A1
 1070 FORMAT(1X,A10,F15.5)
      DO 4 I=1,35
      IF(INSTR(I).EQ.INS) GO TO 6
    4 CONTINUE
      STOP 4
C
C       I =  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20
C
    6 GO TO(11,11,11,20,20,20,30,30,30,30,40,40,50,50,50,50,60,60,60,60,
C
C        21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
C
     1 70,70,80,80,81,82,82,82,83,84,84,86,86,86,86),I
C
C         INPUT THE COLLAPSE FIELD HC.  KMAG = 1
C
   11 HC=A1
      NMAG=NMAG+1
      KMAG(NMAG)=1
      IF(NLEN.GE.1.AND.NMAG.GE.1.AND.NLEN+NMAG.EQ.3) GO TO 90
      GO TO 1
C
C         INPUT THE STRIPOUT FIELD HS.  KMAG = 2
C
   20 HS=A1
      NMAG=NMAG+1
      KMAG(NMAG)=2
      IF(NLEN.GE.1.AND.NMAG.GE.1.AND.NLEN+NMAG.EQ.3) GO TO 90
      GO TO 1
```

```
C
C      INPUT THE THICKNESS H.  KLEN = 1
C
   30 H=A1
      NLEN=NLEN+1
      KLEN(NLEN)=1
      IF(NLEN.GE.1.AND.NMAG.GE.1.AND.NLEN+NMAG.EQ.3) GO TO 90
      GO TO 1
C
C      INPUT THE SUSCEPTIBILITY TIMES THICKNESS XOH.  KLEN = 2
C
   40 XOH=A1
      NLEN=NLEN+1
      KLEN(NLEN)=2
      IF(NLEN.GE.1.AND.NMAG.GE.1.AND.NLEN+NMAG.EQ.3) GO TO 90
      GO TO 1
C
C      INPUT THE STRIPEWIDTH SW.  KLEN = 3
C
   50 SW=A1
      NLEN=NLEN+1
      KLEN(NLEN)=3
      IF(NLEN.GE.1.AND.NMAG.GE.1.AND.NLEN+NMAG.EQ.3) GO TO 90
      GO TO 1
C
C      INPUT THE SATURATION MAGNETIZATION MS.  KMAG = 3
C
   60 MS=A1
      NMAG=NMAG+1
      KMAG(NMAG)=3
      IF(NLEN.GE.1.AND.NMAG.GE.1.AND.NLEN+NMAG.EQ.3) GO TO 90
      GO TO 1
C
C      INPUT THE CHARACTERISTIC LENGTH L.  KLEN = 4
C
   70 L=A1
      NLEN=NLEN+1
      KLEN(NLEN)=4
      IF(NLEN.GE.1.AND.NMAG.GE.1.AND.NLEN+NMAG.EQ.3) GO TO 90
      GO TO 1
C
C      INPUT THE SUSCEPTIBILITY XO.  KMAG = 4
C
   80 XO=A1
      NMAG=NMAG+1
      KMAG(NMAG)=4
      IF(NLEN.GE.1.AND.NMAG.GE.1.AND.NLEN+NMAG.EQ.3) GO TO 90
      GO TO 1
C
C      INPUT THE QUALITY FACTOR Q      KIPM = 1
C
   81 Q=A1
      KIPM=1
      IF(MS.NE.0.) GO TO 140
      GO TO 1
C
C      INPUT THE ANISOTROPY FIELD HK      KIPM = 2
```

```
C
   82 HK=A1
      KIPM=2
      IF(MS.NE.0.) GO TO 130
      GO TO 1
C
C         INPUT THE ANISOTROPY ENERGY DENSITY KU       KIPM = 3
C
   83 KU=A1
      KIPM=3
      IF(MS.NE.0.) GO TO 125
      GO TO 1
C
C         INPUT MAGNETIZATION DETERMINED FROM COLLAPSE FIELD
C         USING THE CALLEN AND JOSEPHS APPROXIMATION      KMAG = 5
C
   84 CJM=A1
      NMAG=NMAG+1
      KMAG(NMAG)=5
      IF(NLEN.GE.1.AND.NMAG.GE.1.AND.NLEN+NMAG.EQ.3) GO TO 90
      GO TO 1
C
C         INPUT AN IDENTIFYING LABEL.
C
   85 BACKSPACE 5
      READ(5,961) LABEL
      GO TO 1
C
C         INPUT THE FIELD FOR HALF-SATURATION MAGNETIZATION KMAG = 6
C
   86 H12=A1
      NMAG=NMAG+1
      KMAG(NMAG)=6
      IF(NLEN.GE.1.AND.NMAG.GE.1.AND.NLEN+NMAG.EQ.3) GO TO 90
      GO TO 1
   90 IF(KMAG(1).EQ.1.AND.KMAG(2).EQ.0) GO TO 101
      IF((KMAG(1).EQ.1.AND.KMAG(2).EQ.2).OR.(KMAG(1).EQ.2.AND.KMAG(2)
     1 .EQ.1)) GO TO 99
      IF((KMAG(1).EQ.1.AND.KMAG(2).EQ.3).OR.(KMAG(1).EQ.3.AND.KMAG(2)
     1  .EQ.1)) GO TO 98
      IF((KMAG(1).EQ.1.AND.KMAG(2).EQ.4).OR.(KMAG(1).EQ.4.AND.KMAG(2)
     1 .EQ.1)) GO TO 97
      IF(KMAG(1).EQ.2.AND.KMAG(2).EQ.0) GO TO 101
      IF((KMAG(1).EQ.2.AND.KMAG(2).EQ.3).OR.(KMAG(1).EQ.3.AND.KMAG(2)
     1 .EQ.2)) GO TO 95
      IF((KMAG(1).EQ.2.AND.KMAG(2).EQ.4).OR.(KMAG(1).EQ.4.AND.KMAG(2)
     1 .EQ.2)) GO TO 94
      IF(KMAG(1).EQ.3.AND.KMAG(2).EQ.0) GO TO 101
      IF((KMAG(1).EQ.3.AND.KMAG(2).EQ.4).OR.(KMAG(1).EQ.4.AND.KMAG(2)
     1 .EQ.3)) GO TO 92
      IF(KMAG(1).EQ.4.AND.KMAG(2).EQ.0) GO TO 101
      IF(KMAG(1).EQ.5.AND.KMAG(2).EQ.0) GO TO 103
      IF(KMAG(1).EQ.6.AND.KMAG(2).EQ.0) GO TO 104
      STOP "90"
C
C         XO AND MS WERE INPUT.  KMAG = 3 AND 4
C
```

```
   92 CALL LAGINT(X0,CHI0,DI,HCBYMS,HCOVMS,40)
      CALL LAGINT(X0,CHI0,DI,HSBYMS,HSOVMS,40)
      CALL LAGINT(X0,CHI0,DI,LOVH,LOH,40)
      CALL LAGINT(X0,CHI0,DI,WOVH,WOH,40)
      CALL LAGINT(LOH,LOVH,DI,HHALF,H12OVM,40)
      HC=HCOVMS*MS
      HS=HSOVMS*MS
      GO TO 102
C
C     X0 AND HS WERE INPUT.  KMAG = 2 AND 4
C
   94 CALL LAGINT(X0,CHI0,DI,HSBYMS,HSOVMS,40)
      CALL LAGINT(X0,CHI0,DI,HCBYMS,HCOVMS,40)
      CALL LAGINT(X0,CHI0,DI,LOVH,LOH,40)
      CALL LAGINT(X0,CHI0,DI,WOVH,WOH,40)
      CALL LAGINT(LOH,LOVH,DI,HHALF,H12OVM,40)
      MS=HS/HSOVMS
      HC=HCOVMS*MS
      GO TO 102
C
C     HS AND MS WERE INPUT.  KMAG = 2 AND 3
C
   95 HSOVMS=HS/MS
      CALL LAGINT(HSOVMS,HSBYMS,DI,HCBYMS,HCOVMS,40)
      CALL LAGINT(HSOVMS,HSBYMS,DI,LOVH,LOH,40)
      CALL LAGINT(HSOVMS,HSBYMS,DI,WOVH,WOH,40)
      CALL LAGINT(HSOVMS,HSBYMS,DI,CHI0,X0,40)
      CALL LAGINT(LOH,LOVH,DI,HHALF,H12OVM,40)
      HC=HCOVMS*MS
      GO TO 102
C
C     X0 AND HC WERE INPUT.  KMAG = 1 AND 4
C
   97 CALL LAGINT(X0,CHI0,DI,HCBYMS,HCOVMS,40)
      CALL LAGINT(X0,CHI0,DI,HSBYMS,HSOVMS,40)
      CALL LAGINT(X0,CHI0,DI,LOVH,LOH,40)
      CALL LAGINT(X0,CHI0,DI,WOVH,WOH,40)
      CALL LAGINT(LOH,LOVH,DI,HHALF,H12OVM,40)
      MS=HC/HCOVMS
      HS=HSOVMS*MS
      GO TO 102
C
C     HC AND MS WERE INPUT.  KMAG = 1 AND 3
C
   98 HCOVMS=HC/MS
      CALL LAGINT(HSOVMS,HCBYMS,DI,WOVH,WOH,40)
      CALL LAGINT(HCOVMS,HCBYMS,DI,LOVH,LOH,40)
      CALL LAGINT(HCOVMS,HCBYMS,DI,HSBYMS,HSOVMS,40)
      CALL LAGINT(HSOVMS,HCBYMS,DI,CHI0,X0,40)
      CALL LAGINT(LOH,LOVH,DI,HHALF,H12OVM,40)
      HS=HSOVMS*MS
      GO TO 102
C
C     HC AND HS WERE INPUT.  KMAG = 1 AND 2
C
   99 HCOVHS=HC/HS
      CALL LAGINT(HCOVHS,HCBYHS,DI,LOVH,LOH,40)
```

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      CALL LAGINT(HCOVHS,HCBYHS,DI,WOVH,WOH,40)                         BUBCH343
      CALL LAGINT(HCOVHS,HCBYHS,DI,HCBYMS,HCOVMS,40)                    BUBCH344
      CALL LAGINT(HCOVHS,HCBYHS,DI,HSBYMS,HSOVMS,40)                    BUBCH345
      CALL LAGINT(HCOVHS,HCBYHS,DI,CHI0,X0,40)                          BUBCH346
      CALL LAGINT(LOH,LOVH,DI,HHALF,H12OVM,40)                          BUBCH347
      MS=(HC/HCOVMS+HS/HSOVMS)*0.5                                      BUBCH348
      GO TO 102                                                         BUBCH349
  101 IF((KLEN(1).EQ.1.AND.KLEN(2).EQ.2).OR.(KLEN(1).EQ.2.AND.KLEN(2)   BUBCH350
     1 .EQ.1)) GO TO 112                                                BUBCH351
      IF((KLEN(1).EQ.1.AND.KLEN(2).EQ.3).OR.(KLEN(1).EQ.3.AND.KLEN(2)   BUBCH352
     1 .EQ.1)) GO TO 111                                                BUBCH353
      IF((KLEN(1).EQ.1.AND.KLEN(2).EQ.4).OR.(KLEN(1).EQ.4.AND.KLEN(2)   BUBCH354
     1 .EQ.1)) GO TO 110                                                BUBCH355
      IF((KLEN(1).EQ.2.AND.KLEN(2).EQ.3).OR.(KLEN(1).EQ.3.AND.KLEN(2)   BUBCH356
     1 .EQ.2)) GO TO 109                                                BUBCH357
      IF((KLEN(1).EQ.2.AND.KLEN(2).EQ.4).OR.(KLEN(1).EQ.4.AND.KLEN(2)   BUBCH358
     1 .EQ.2)) GO TO 108                                                BUBCH359
      IF((KLEN(1).EQ.3.AND.KLEN(2).EQ.4).OR.(KLEN(1).EQ.4.AND.KLEN(2)   BUBCH360
     1 .EQ.3)) GO TO 107                                                BUBCH361
      STOP 101                                                          BUBCH362
  102 IF(KLEN(1).EQ.1) GO TO 113                                        BUBCH363
      IF(KLEN(1).EQ.2) GO TO 114                                        BUBCH364
      IF(KLEN(1).EQ.3) GO TO 115                                        BUBCH365
      IF(KLEN(1).EQ.4) GO TO 116                                        BUBCH366
      STOP 102                                                          BUBCH367
  103 IF((KLEN(1).EQ.1.AND.KLEN(2).EQ.3).OR.(KLEN(1).EQ.3.AND.KLEN(2).EQBUBCH368
     1.1)) GO TO 1221                                                   BUBCH369
      STOP 103                                                          BUBCH370
  104 IF((KLEN(1).EQ.1.AND.KLEN(2).EQ.3).OR.(KLEN(1).EQ.3.AND.KLEN(2)   BUBCH371
     1 .EQ.1)) GO TO 1222                                               BUBCH372
      STOP 104                                                          BUBCH373
C                                                                       BUBCH374
C        SW AND L WERE INPUT.   KLEN = 3 AND 4                          BUBCH375
C                                                                       BUBCH376
  107 CALL LAGINT(-SW/L,WOVH,LOVH,LOVH,LOH,40)                          BUBCH377
      CALL LAGINT(LOH,LOVH,DI,HCBYMS,HCOVMS,40)                         BUBCH378
      CALL LAGINT(LOH,LOVH,DI,HSBYMS,HSOVMS,40)                         BUBCH379
      CALL LAGINT(LOH,LOVH,DI,CHI0,X0,40)                               BUBCH380
      CALL LAGINT(LOH,LOVH,DI,HHALF,H12OVM,40)                          BUBCH381
      H=L/LOH                                                           BUBCH382
      GO TO 117                                                         BUBCH383
C                                                                       BUBCH384
C        L AND X0H WERE INPUT.   KLEN = 2 AND 4                         BUBCH385
C                                                                       BUBCH386
  108 CALL LAGINT(-X0H/L,CHI0,LOVH,LOVH,LOH,40)                         BUBCH387
      CALL LAGINT(LOH,LOVH,DI,WOVH,WOH,40)                              BUBCH388
      CALL LAGINT(LOH,LOVH,DI,CHI0,X0,40)                               BUBCH389
      CALL LAGINT(LOH,LOVH,DI,HCBYMS,HCOVMS,40)                         BUBCH390
      CALL LAGINT(LOH,LOVH,DI,HSBYMS,HSOVMS,40)                         BUBCH391
      CALL LAGINT(LOH,LOVH,DI,HHALF,H12OVM,40)                          BUBCH392
      H=X0H/X0                                                          BUBCH393
      SW=WOH*H                                                          BUBCH394
      GO TO 117                                                         BUBCH395
C                                                                       BUBCH396
C        X0H AND SW WERE INPUT.   KLEN = 2 AND 3                        BUBCH397
C                                                                       BUBCH398
  109 CALL LAGINT(-X0H/SW,CHI0,WOVH,LOVH,LOH,40)                        BUBCH399
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```
      CALL LAGINT(LOH,LOVH,DI,WOVH,WOH,40)
      CALL LAGINT(LOH,LOVH,DI,CHI0,XO,40)
      CALL LAGINT(LOH,LOVH,DI,HCBYMS,HCOVMS,40)
      CALL LAGINT(LOH,LOVH,DI,HSBYMS,HSOVMS,40)
      CALL LAGINT(LOH,LOVH,DI,HHALF,H12OVM,40)
      H=XOH/XO
      SW=WOH*H
      GO TO 117
C
C         H AND L WERE INPUT.  KLEN = 1 AND 4
C
  110 LOH=L/H
      CALL LAGINT(LOH,LOVH,DI,HSBYMS,HSOVMS,40)
      CALL LAGINT(LOH,LOVH,DI,HCBYMS,HCOVMS,40)
      CALL LAGINT(LOH,LOVH,DI,CHI0,XO,40)
      CALL LAGINT(LOH,LOVH,DI,WOVH,WOH,40)
      CALL LAGINT(LOH,LOVH,DI,HHALF,H12OVM,40)
      SW=WOH*H
      GO TO 117
C
C         H AND SW WERE INPUT.  KLEN = 1 AND 3
C
  111 WOH=SW/H
      CALL LAGINT(WOH,WOVH,DI,HSBYMS,HSOVMS,40)
      CALL LAGINT(WOH,WOVH,DI,HCBYMS,HCOVMS,40)
      CALL LAGINT(WOH,WOVH,DI,CHI0,XO,40)
      CALL LAGINT(WOH,WOVH,DI,LOVH,LOH,40)
      CALL LAGINT(LOH,LOVH,DI,HHALF,H12OVM,40)
      L=LOH*H
      GO TO 117
C
C         H AND XOH WERE INPUT.  KLEN = 1 AND 2
C
  112 XO=XOH/H
      CALL LAGINT(XO,CHI0,DI,HSBYMS,HSOVMS,40)
      CALL LAGINT(XO,CHI0,DI,HCBYMS,HCOVMS,40)
      CALL LAGINT(XO,CHI0,DI,WOVH,WOH,40)
      CALL LAGINT(XO,CHI0,DI,LOVH,LOH,40)
      CALL LAGINT(LOH,LOVH,DI,HHALF,H12OVM,40)
      L=LOH*H
      SW=WOH*H
      GO TO 117
C
C         H WAS INPUT      KLEN = 1
C
  113 L=LOH*H
      SW=WOH*H
      GO TO 122
C
C         XOH WAS INPUT      KLEN = 2
C
  114 H=XOH/XO
      L=LOH*H
      SW=WOH*H
      GO TO 122
C
C         SW WAS INPUT      KLEN = 3
```

```
C
  115 H=SW/WOH
      L=LOH*H
      GO TO 122
C
C         L WAS INPUT      KLEN = 4
C
  116 H=L/LOH
      SW=WOH*H
      GO TO 122
C
C      SELECT THE MAGNETIC PARAMETERS YET TO BE CALCULATED
C
  117 IF(NMAG.GT.1) STOP 117
      IF(KMAG(1).EQ.1) GO TO 118
      IF(KMAG(1).EQ.2) GO TO 119
      IF(KMAG(1).EQ.3) GO TO 120
      IF(KMAG(1).EQ.4) GO TO 121
      STOP 1170
C
C         HC WAS INPUT      KMAG = 1
C
  118 MS=HC/HCOVMS
      HS=HSOVMS*MS
      GO TO 122
C
C         HS WAS INPUT      KMAG = 2
C
  119 MS=HS/HSOVMS
      HC=HCOVMS*MS
      GO TO 122
C
C         MS WAS INPUT      KMAG = 3
C
  120 HC=HCOVMS*MS
      HS=HSOVMS*MS
      GO TO 122
C
C         XO WAS INPUT      KMAG = 4
C
  121 WRITE(6,1010) XO,H,SW,L,HCOVMS,HSOVMS
 1010 FORMAT(/" XO WAS THE ONLY MAGNETIC PARAMETER INPUT"/" XO = "E12.6
     1 ", H = "E12.6", SW = "E12.6", AND L = "E12.6"."/" ALL THAT CAN BE
     2 SAID ABOUT THE OTHER MAGNETIC PARAMETERS IS:"/" HC/4.PI.MS = "
     3 E12.6" AND HS/4.PI.MS = "E12.6"."//)
      GO TO 10
C
C         CALLEN AND JOSEPHS MAGNETIZATION, STRIPEWIDTH, AND THICKNESS
C         WERE INPUT.  CALCULATE HC, SET KMAG TO 1, AND GO TO 111.
C
 1221 WOH=SW/H
      CALL LAGINT(WOH,WOVH,DI,LOVH,LOH,40)
      HC=(1.+0.75*LOH-SQRT(3.*LOH))*CJM
      KMAG(1)=1
      GO TO 111
C
C         LASER SPATIAL FILTERING CHARACTERIZATION.
```

```
C       FIELD (H12) FOR HALF-SATURATION MAGNETIZATION,
C       THICKNESS, AND ZERO-MAGNETIZATION STRIPEWIDTH WERE INPUT.
C
C       CALLEN AND JOSEPHS APPROXIMATE ANALYSIS IS ASSUMED AND
C       CORRECTED BY THIELE ANALYSIS USING DERIVED BUBBLE COLLAPSE
C       FIELD
C
 1222 WOH=SW/H
      CALL LAGINT(WOH,WOVH,DI,HHALF,H12OVM,40)
      CJM=H12/H12OVM
      GO TO 1221
  122 CONTINUE
      H12=H12OVM*MS
      WALL=MS*MS*L/PI4
      WALL=WALL*1.E-4
      WRITE(6,1000) LABEL,H,L,X0,SW,MS,HS,HC,WALL,H12
 1000 FORMAT(/1X,8A10/" H = "E12.6", L = "E12.6", CHI0 = "E12.6", SW = "
     1 E12.6/" 4.PI.MS = "E12.6", HS = "E12.6", HC = "E12.6", BULK WALL
     2ENERGY = "E12.6/" H1/2 (FIELD FOR HALF-SATURATION MAGNETIZATION) =
     3 "E12.6//)
      CALL STABLT(LOH,H,MS)
      IF(KIPM.NE.0) GO TO 124
      READ(5,960) INS
      IF(EOF(5)) 100,123
  123 BACKSPACE 5
      IF(INS.EQ."Q".OR.INS.EQ."HU".OR.INS.EQ."HA".OR.INS.EQ."HK".OR.
     1 INS.EQ."KU") GO TO 10
      GO TO 9
  124 CONTINUE
      WRITE(6,1090)
 1090 FORMAT(/10X"IN-PLANE PARAMETERS (ACCORDING TO DEBONTE) FOLLOW:"//)
      IF(KIPM.EQ.1) GO TO 140
      IF(KIPM.EQ.2) GO TO 130
C
C       ANISOTROPY ENERGY DENSITY KU WAS INPUT      KIPM = 3
C
  125 CONTINUE
      HK=2.*KU*PI4/MS
      Q=HK/MS
      GO TO 150
C
C       ANISOTROPY FIELD HK WAS INPUT      KIPM = 2
C
  130 Q=HK/MS
      KU=0.5*MS*HK/PI4
      GO TO 150
C
C       QUALITY FACTOR Q WAS INPUT      KIPM = 1
C
  140 HK=Q*MS
      KU=0.5*MS*HK/PI4
C
C       COMPUTE THE REMAINING INPLANE PARAMETERS
C
  150 EXCONS=WALL*WALL/(16.*KU)
      CDASH1=Q/LOH
      CALL LAGRGE(CDASH1,PHI1,Y1)
```

```
      CALL LAGRGE(CDASH1,EDASH,Y2)
      CALL LAGRGE(CDASH1,RATIO,Y3)
      ALENTH=(PI4*0.25/Y3)*SQRT(EXCONS/KU)*10000.
      Y11=Y1*720./PI4
      Y2=Y2*2.0*SQRT(KU*EXCONS)
      WRITE(6,1080) Y11,Y1,Y2,ALENTH,Q,KU,HK,EXCONS
 1080 FORMAT(////"  MAXIMUM TWIST ANGLE"13(".")"="F8.4,3X"DEGREES"3X,
     1 "("F5.2"  RAD.)"/"  DOMAIN WALL ENERGY"14(".")"="E14.6,3X,
     2 3X"ERGS/SQ.CM."/"  WALL THICKNESS"18(".")"="E14.6,3X
     3 "MICRONS"/"  Q = "F10.3", KU = "E12.6", HK = "E12.6", AND EXCHANG
     4E CONSTANT = "E12.6)
      MS=0.
      GO TO 10
  100 STOP
      END
      SUBROUTINE LAGINT(X,ARG1,ARG2,VAL,Y,NDIM)
C
C           THIS IS THE SUBROUTINE WHICH PERFORMS THE 4-POINTS
C           LAGRANGES INTERPRETATION FOR THE DATA
C
      DIMENSION ARG1(56),ARG2(56),VAL(56),RR(56)
      DO 10 J=1,56
   10 RR(J)=0.
      IF(X.LT.0.) GO TO 6
      DO 1 I=1,NDIM
      IF(ARG1(I).EQ.0..AND.X.NE.0.) GO TO 1
      IF(ARG2(I).LT.1.E-6) ARG2(I)=1.E-6
      IF(ARG1(I)/ARG2(I)-X) 1,2,3
    1 CONTINUE
    2 Y=VAL(I)
      RETURN
    3 IPIV=I
      IF(IPIV.EQ.2) MIN=1
      IF(IPIV.GT.2) MIN=IPIV-2
      MAX=IPIV+1
      IF(MIN.LT.1) MIN=1
      IF(MIN.GT.NDIM) MIN=NDIM
      IF(MAX.GT.NDIM) MAX=NDIM
      IF(MAX.LT.MIN) MAX=MIN
      DO 4 N=MIN,MAX
      RR(N)=1.
      DO 4 I=MIN,MAX
      IF(N.EQ.I) GO TO 4
      IF(ABS(ARG1(N)/ARG2(N)-ARG1(I)/ARG2(I)).LE.1.E-6) GO TO 4
      RR(N)=RR(N)*(X-ARG1(I)/ARG2(I))/(ARG1(N)/ARG2(N)-ARG1(I)/ARG2(I))
    4 CONTINUE
      Y=0.
      DO 5 I=MIN,MAX
    5 Y=Y+RR(I)*VAL(I)
      RETURN
    6 X=ABS(X)
      DO 7 I=1,NDIM
      IF(ARG1(I).EQ.0..AND.X.NE.0.) GO TO 7
      IF(ARG2(I).LT.1.E-6) ARG2(I)=1.E-6
      IF(ARG1(I)/ARG2(I)-X) 3,2,7
    7 CONTINUE
      STOP" SUBROUTINE LAGINT FAILED"
```

```
      END
      SUBROUTINE STABLT(LOH,D,SAT)
C
C               THIS IS THE SUBROUTINE WHICH GIVES THE OPERATING POINTS
C               FOR THE BUBBLE DOMAINS AS WELL AS THE COLLAPSE AND THE
C               RUNOUT DIAMETERS AND FIELDS
C
      DIMENSION DI(56)
      DIMENSION A(56),F(56),S0(56),S2(56),DIM(15),HAPP(15)
      REAL LOH
      DATA DI/56*1./
      DATA A/0.00,0.10,0.20,0.30,0.40,0.50,0.60,0.70,0.80,0.90,1.00,1.10
     1 ,1.2,1.3,1.4,1.5,1.6,1.7,1.8,1.9,2.,2.1,2.2,2.3,2.4,2.5,2.6,
     2 2.7,2.8,2.9,3.,3.2,3.4,3.6,3.8,4.,4.2,4.4,4.6,4.8,5.,5.2,5.4,
     3 5.6,5.8,6.,6.2,6.4,6.6,6.8,7.,7.2,7.4,7.6,7.8,8./
     0DATA F/0.,.0939,.1765,.2493,.3137,.3708,.4216,.4672,.5083,
     1 .5455,.5794,.6104,.6390,.6655,.6901,.7130,.7345,.7547,.7737,
     2 .7917,.8087,.8249,.8404,.8551,.8692,.8827,.8956,.9081,.9200,
     3 .9316,.9427,.9639,.9837,1.0024,1.0201,1.0368,1.0526,1.0678,
     4 1.0822,1.0960,1.1092,1.1219,1.1341,1.1458,1.1572,1.1681,1.1787,
     5 1.1889,1.1988,1.2084,1.2177,1.2268,1.2356,1.2442,1.2525,1.2606/
      DATA S0/0.,.0059,.0215,.0442,.0716,.1017,.1332,.1648,.1960,.2262
C    ,.2552
     1 ,.2829,.3093,.3343,.3579,.3804,.4016,.4218,.4410,.4592,.4765,
     2 .4931,.5089,.5240,.5385,.5524,.5657,.5786,.5909,.6028,.6143,.6362
     3 ,.6566,.6759,.6940,.7112,.7275,.7430,.7578,.7720,.7855,.7985,
     4 .8109,.8229,.8345,.8456,.8564,.8668,.8769,.8866,.8961,.9053,
     5 .9142,.9229,.9314,.9396/
      DATA S2/0.,.0007,.0028,.0063,.0111,.0172,.0243,.0323,.0411,.0505,
     1 0.0603,.0705,.0809,.0914,.1020,.1126,.1231,.1336,.1439,.1541,
     2 .1642,.1741,.1838,.1933,.2027,.2119,.2209,.2297,.2838,.2468,
     3 .2551,.2712,.2866,.3051,.3158,.3295,.3428,.3556,.3679,.3799,
     4 .3914,.4026,.4134,.4239,.4341,.4439,.4535,.4629,.4720,.4808,.4894
     5 , .4978,.5060,.5140,.5218,.5295/
      D=D*1.E-4
      HL=1./LOH
      HHL=1./HL
      CALL LAGINT(HHL,S0,DI,A,X0,56)
      CALL LAGINT(HHL,S2,DI,A,X2,56)
      STEP=(X2-X0)/10.
      WRITE(6,10)
   10 FORMAT(1X,52("-"),/," BUBBLE DIAMETER (MICRONS)",10X,
     1 "APPLIED FIELD (OE)",/,1X,52("-"))
      DIM(1)=X0*D
      ASPECT=X0
      DO 20 I=1,11
      CALL LAGINT(ASPECT,A,DI,F,YF,56)
      HAPP(I)=SAT*(YF-HHL)/ASPECT
      DIMI=DIM(I)*10000.
      HAPPI=HAPP(I)
      IF(I.EQ.1.OR.I.EQ.11) GO TO 35
      WRITE(6,30) DIMI,HAPPI
   30 FORMAT(11X,F6.2,24X,F6.2)
   35 ASPECT=ASPECT+STEP
   20 DIM(I+1)=ASPECT*D
      DIM(1)=DIM(1)*10000.
      DIM(11)=DIM(11)*10000.
```

```
      WRITE(6,40) DIM(1),HAPP(1),DIM(11),HAPP(11)
   40 FORMAT(1X,52("-"),//,"  BUBBLE COLLAPSE DIAMETER =  ",F6.2,2X,
     1 "MICRONS",/,2X,"BUBBLE COLLAPSE FIELD       =  "F6.2," OERSTEDS",/,
     2 "  BUBBLE RUNOUT DIAMETER    =  ",F6.2,"  MICRONS",/,
     3"  BUBBLE RUNOUT FIELD         =  ",F6.2," OERSTEDS"5(/))
      D=D*1.E4
   80 RETURN
      END
      SUBROUTINE LAGRGE(X,VAL,Y)
C
C           THIS IS THE SUBROUTINE WHICH PERFORMS THE 4-POINTS
C           LAGRANGES INTERPOLATION FOR THE DATA OF DEBONTE..
C
      DIMENSION ARG(30),VAL(120),RR(30)
      COMMON /AA/QU
C
C      IN SUBROUTINE LAGRGE, "ARG" IS THE DEBONTE FUNCTION C'
C
      DATA   ARG/.1,.15,.2,.3,.4,.5,.6,.7,.8,.9,1.,1.5,2.,3.,4.,5.,6.,7.
     1 ,8.,9.,10.,15.,20.,30.,40.,50.,60.,70.,80.,90./
      DO 10 J=1,30
   10 RR(J)=0.
      DO 1 K=1,30
      I=K
      IF(ARG(I)-X)1,2,3
    1 CONTINUE
    2 IWW=1
      GO TO 6
    3 IWW=2
    6 IF(QU.LT.1.28) J=0
      IF(QU.GE.1.28.AND.QU.LE.1.65) J=30
      IF(QU.GT.1.65.AND.QU.LE.3.0) J=60
      IF(QU.GT.3.) J=90
      IF(IWW.EQ.2) GO TO 7
      Y=VAL(I+J)
      GO TO 8
    7 IF(I.LT.3) GO TO 74
      MIN=I-2
      MAX=I+1
      IF(MAX.GT.30) GO TO 76
      GO TO 78
   74 MIN=1
      MAX=4
      GO TO 78
   75 MAX=30
      MIN=27
   78 CONTINUE
      DO 4 N=MIN,MAX
      RR(N)=1.
      DO 4 I=MIN,MAX
      IF(N.EQ.I) GO TO 4
       IF(ABS(ARG(N)-ARG(I)).LE.0.00001) GO TO 4
      RR(N)=RR(N)*((X-ARG(I))/(ARG(N)-ARG(I)))
    4 CONTINUE
      Y=0.0
      DO 5 I=MIN,MAX
      M=J+I
```

```
5     Y=Y+RR(I)*VAL(M)                                                  LAGRG 50
 8    CONTINUE                                                          LAGRG 51
      RETURN                                                            LAGRG 52
      END                                                               LAGRG 53
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